Iris Lewandowski · Lina Mayorga-Duarte ·
Philipp Scheurich · Ricardo Vargas-Carpintero ·
Valentin Schlecht · Jan Weik *Editors*

Bioeconomy

Advancing the Transition to a Sustainable, Biobased Economy

Second Edition

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UNIVERSITY OF HOHENHEIM

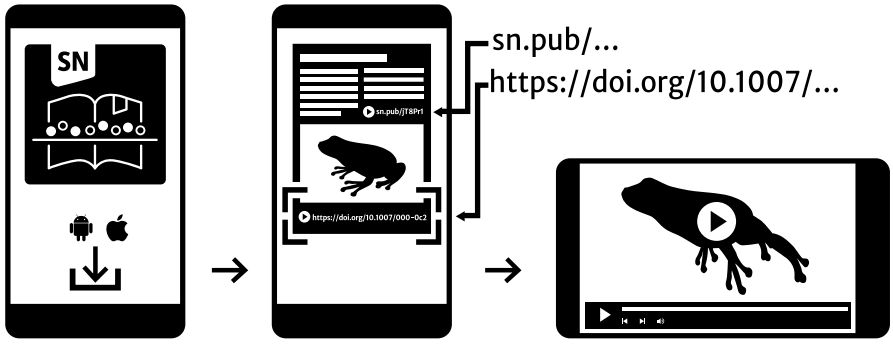
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This textbook is dedicated to Prof. Dr. Stephan Dabbert, President of the University of Hohenheim, who sadly passed away on October 1, 2024, while this book underwent editorial revision. Prof. Dr. Dabbert was always a strong advocate of the bioeconomy in research and teaching at the University of Hohenheim. His visionary leadership and unwavering commitment to striving for the best for Hohenheim will continue to inspire us all.

Preface

In October 2014, the master's programme "Bioeconomy" was launched as a joint master's programme of all three faculties of the University of Hohenheim, i.e. the Faculty of Agricultural Sciences, the Faculty of Natural Sciences and the Faculty of Business, Economics and Social Sciences. The concept of the Bioeconomy master's programme is based on an integrated approach to a circular, sustainable bioeconomy system that operates within the planetary boundaries and explicitly takes the needs of people into account. To realise this concept, we developed a T-shaped profile (Fig. 1), which illustrates how students from different disciplinary backgrounds learn together and acquire inter- and transdisciplinary skills as well as sustainability and transformative knowledge.

The first edition of this textbook, which was designed and authored by students and teachers involved in the master's programme, was published in 2018. Since then, the global bioeconomy has evolved into an operational approach to sustainability. Novel and innovative technologies for the production, supply, conversion and utilisation of bio-based resources and biological knowledge have been developed, as have more than 70 bioeconomy strategies at various levels, including national, regional and local scales. As a result, the knowledge base of the bioeconomy as described in this textbook has expanded.

The desire to acknowledge these developments, update the content and explore new possibilities of incorporating interactive elements inspired the development of a second edition of the bioeconomy textbook. The general structure of the textbook has been retained from the first edition, featuring an exploration along the bio-based value chain,

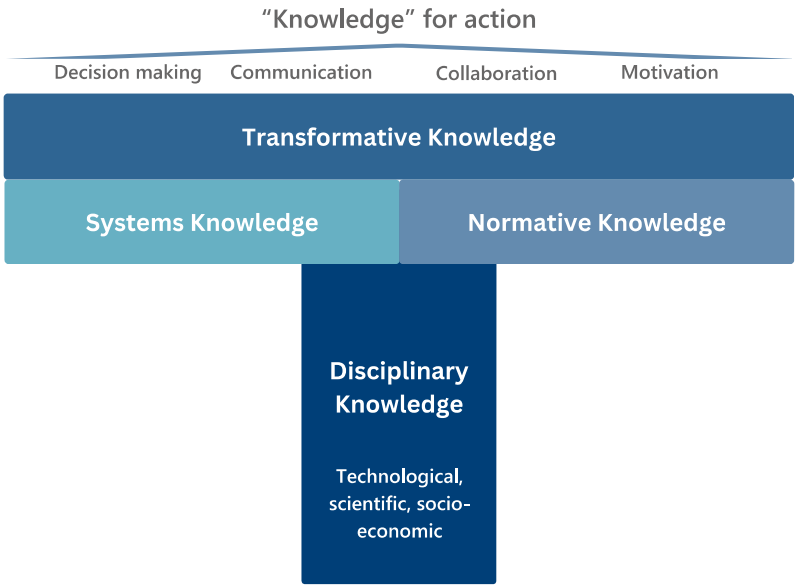


Fig. 1 T-shaped qualification profile

reflecting the inter- and transdisciplinary nature of the bioeconomy. The content covers the production and supply of biomass, its processing and conversion into various products, as well as the associated markets. This is contextualised through transdisciplinary insights on, for instance, bioeconomy systems, innovation, sustainability and governance.

In this second edition, all chapters have been updated and reorganised to enhance coherence and depth. This includes an expanded number of chapters on various biomass sources and processing technologies as well as new chapters on bioeconomy principles, the normative aspects of the bioeconomy, and bioeconomy monitoring. Additionally, a dedicated section explores diverse stakeholder perspectives, covering insights from farmers, consumers, researchers and others. Notably, this edition features interactive elements, with supplementary digital content to enrich the learning experience.

While this textbook attempts to provide a comprehensive overview of the topic, the scope of the bioeconomy is oftentimes intangible. A central aim of the textbook is therefore to provide simplicity alongside all the complexity involved. The description of the bioeconomy presented in this textbook is based on the understanding that a growing global population has an increasing demand for healthy food and renewable resources. The main goal of the bioeconomy is hence to find solutions to provide these goods in the best possible way.

The bioeconomy makes use of renewable, bio-based resources and biological knowledge. It applies tools from biotechnology and biomanufacturing, as well as biorefinery approaches. It builds on and further develops technological and societal innovations and nature-based solutions. It delivers not only food and bio-based products but also ecosystem services. It is based on a set of principles, including sustainability and circularity, and applies holistic and systems approaches. Life-cycle thinking is at its core, as are the principles of integrated value webs and multifunctionality. The bioeconomy provides practical solutions for dealing with societal challenges and supports the sustainability transformation (Fig. 2).

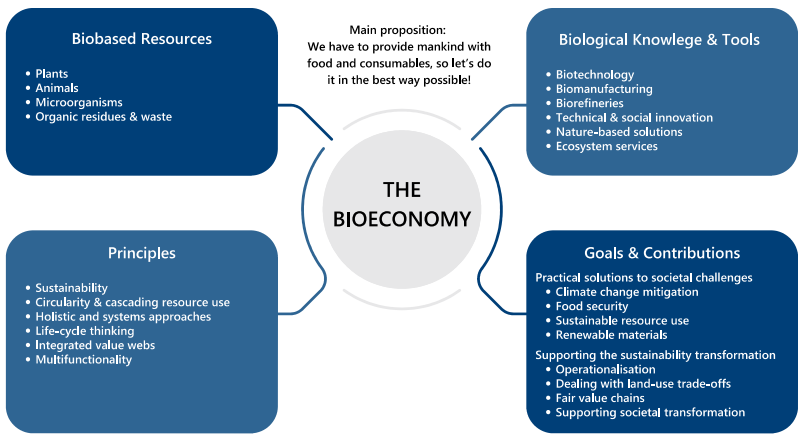


Fig. 2 Description of the bioeconomy

As the field of the bioeconomy is broad, the content of this textbook extends well beyond the topics taught in the University of Hohenheim's two-year Bioeconomy master's programme at the University of Hohenheim. In order to cover the entire spectrum of the bioeconomy, experts from outside the university were invited to contribute. As a result, this comprehensive textbook is aimed not only at university students but also addresses other audiences that are keen to learn about the bioeconomy in a systematic way. Both, readers who are interested in a holistic view of the topic and those seeking a deeper insight into a specific aspect of the bioeconomy will find what they are looking for.

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About This Book

Dear reader,

we have carefully designed this textbook to support your learning journey and help you grasp the key concepts of the bioeconomy in an engaging and structured way. While the textbook is primarily aimed at bioeconomy students, its content is designed to be accessible to a wide range of readers. Whether you are studying in a related field or simply interested in gaining a deeper understanding of the bioeconomy, the clear explanations and supporting interactive learning elements make the book suitable for anyone eager to explore the bioeconomy. For this purpose, the textbook is composed of a total of six parts, each of which comprises several chapters designated to common thematic areas:

Part I: Bioeconomy Context, Concepts and Principles

The opening part of the textbook addresses the context and the role of the bioeconomy in contributing solutions to global challenges (▶ Chap. 1). It explains the different concepts of the bioeconomy (▶ Chap. 2) and explores its underlying principles, including sustainability, multidimensionality, multifunctionality, circularity, cascading resource use, inter- and transdisciplinarity, and a holistic systems thinking approach (▶ Chap. 3). The final chapter examines bio-based value chains and webs as the basis of bioeconomy systems (▶ Chap. 4).

Part II: Biomass Production Systems

The bioeconomy harnesses two primary resources: (1) biomass, which originates either directly or indirectly from plants, microorganisms or animals, and (2) biological knowledge. Bioeconomists need to have a deep understanding of these resources in order to effectively devise strategies for resource supply, to determine the most suitable biomass sources for bio-based product chains and to optimise these product chains.

The second part of the textbook therefore begins by examining the origins and characteristics of biomass, as well as the key technologies used to tailor these characteristics. It also sheds light onto the tools of biological knowledge and their application within the bioeconomy (▶ Chap. 5). The mechanisms underpinning primary biomass production systems in agriculture (▶ Chap. 6), including crop and animal production, are explored, alongside forestry (▶ Chap. 8), which, together with agriculture, forms the cornerstone of resource production and supply in the bioeconomy. These sectors represent the main activity of resource production and supply in the bioeconomy and are pivotal in providing biomass for food, feed and for use in material, chemical and energy applications.

Currently, approximately 33% of the Earth's land surface (roughly 4,900 Mha) is devoted to agricultural production, supporting the livelihoods of 2.5 billion people. Forests, covering around 31% of the Earth's land area (about 4.06 billion hectares), house the majority of the planet's terrestrial biodiversity and store almost as much carbon as the atmosphere. The so-called blue bioeconomy, described in ▶ Chap. 9, relies on renewable, living aquatic resources and organisms such as crustaceans, molluscs and finfish from both freshwater and marine systems, as well as micro- and macroalgae. A large proportion of these aquatic resources is derived from natural stocks by capture fishery, although this practice has led to the depletion of certain fish populations. As a result, aquaculture of varying intensity, which by now accounts for more than half of all aquatic food production, has become increasingly vital.

▶ Chapter 7 provides a number of examples from the field of urban agriculture, including so-called 'controlled-environment agriculture' systems. Similarly, the cultivation of microalgae (▶ Chap. 10) and the rearing of insects (▶ Chap. 11) also take place within controlled environments, although most edible insects are still gathered from the wild. ▶ Chapters 12 and 13 deal with the supply of bio-based resources from residual biomass and biogenic waste streams. Biomass produced during primary production and industrial processing is categorised as residual biomass, which may be recovered and valorised within high-value bioeconomy solutions. Biogenic waste, which makes up a significant proportion of municipal waste, may also be converted into valuable biogenic resources if it is properly collected, separated and treated. Anaerobic digestion and composting are the most relevant treatment processes for converting biogenic waste into methane (biogas), fertilisers or soil improvers. ▶ Chapter 14 focusses on the latter and explores how nutrient cycles may be closed by recycling plant nutrients from a variety of organic waste streams or by-products, including animal manure, crop residues, food scraps and even human excrement.

Digital tools are increasingly used to support management processes like precision farming that help to increase productivity as well as an efficient use of agricultural inputs for the benefit of the environment. ▶ Chapter 15 touches upon the evolution and current trends of digital agriculture–especially the integration of artificial intelligence (AI) into agricultural technology. When developing new bio-based products and when trying to assess their market opportunities it is indispensable to correctly calculate all expected unit costs. In ▶ Chap. 16, the economics of primary production are characterised by the specifics of a biological production system with seasonal variations and the requirements of long-term planning.

Part III: Processing

The fundamental idea behind the bioeconomy lies in the transformation of bio-based resources into a diverse array of products across the food, feed, material and energy sectors. Given the distinctive characteristics of bio-based materials, it is crucial to select the most suitable conversion techniques tailored to the specific application at hand. The third section

of this textbook is hence dedicated to an exploration of these conversion methods and technologies. It therefore begins with an examination of the factors influencing the use of bio-based resources and introduces biorefining as an integrative concept for the sustainable industrial processing of biomass (► Chap. 17). Biorefineries employ a variety of biomass processing pathways, including biotechnological (► Chap. 18) and thermochemical (► Chap. 19) conversion processes. Given that food supply represents the most traditional and, indeed, the most essential function of bio-based resources, ► Chap. 20 offers fundamental knowledge on food quality and food processing techniques, while ► Chap. 21 delves specifically into the production of so-called analogues, i.e. plant-based alternatives to meat and dairy products. The use of bio-based side streams as raw materials for the food industry as well as relevant side streams and processes for this purpose are described in ► Chap. 22. In order to account for the substantial demand for bio-based fibres for different applications, ► Chap. 23 provides an in-depth overview of their properties and methods for their extraction. Bioenergy, long a traditional use of bio-based resources, is the subject of ► Chap. 24, which examines the growing prominence of modern bioenergy solutions, such as liquid biofuels in the transport sector. As all these conversion processes are increasingly supported by digital technologies, ► Chap. 25 discusses how artificial intelligence (AI) creates new opportunities particularly through the digitalisation of the food supply chain and the emergence of Industry 4.0 for bio-based products. This part concludes with an exploration of process and product cost assessment methodologies in ► Chap. 26, providing vital tools for evaluating the economic viability of bioeconomy initiatives.

Part IV: Markets for Bio-based Products and Economics for a Sustainable Bioeconomy

The fourth part of the textbook takes a closer look at the functioning and status of the global market for bio-based products and the question of how best to allocate scarce resources within the bioeconomy, exploring market interactions with agricultural and food markets, as well as policy instruments designed to steer market developments.

Therefore, ► Chap. 27 examines the market for bio-based resources and products, analysing both established products such as biofuels and emerging products like biochemicals and bioplastics, which are poised to gain significant market acceptance in the future. The chapter discusses the key factors influencing the demand and supply of bio-based products, exploring both the drivers and constraints shaping market dynamics. Additionally, it introduces several policy instruments, such as carbon taxes and blending mandates, that are employed to stimulate the growth and adoption of bio-based products. ► Chapter 28 addresses the challenges and limitations posed by resource scarcity in the bioeconomy, emphasising the importance of optimal allocation of limited resources to ensure sustainability across the economic, social and environmental dimension. To this end, the chapter presents a multi-faceted economic framework essential for advancing a sustainable bioeconomy

by introducing the perspectives of (a) welfare economics, which focuses on maximising social welfare by relying on market mechanisms, (b) environmental economics, which examines market failures, particularly those involving externalities and public goods, and (c) climate and energy economics exploring the bioeconomy's potential to mitigate climate change.

Part V: Stakeholders of the Bioeconomy

The transition to a sustainable economy demands the active involvement of sustainability-conscious stakeholders such as producers and consumers who, through their businesses, capabilities, targeted preferences and choices, steer economic activities in a responsible manner. This transition needs to be steered by supporting policies. Furthermore, research and education are pivotal in developing and fostering innovations, training the work force for the bioeconomy and support the required interactions among the different actors in bioeconomy.

Therefore, the fifth part of this textbook deals with the relevant stakeholder that drive the bioeconomy, including politicians, farmers, entrepreneurs, consumers and researchers. ▶ Chapter 29 provides an in-depth examination of the governance of the bioeconomy, detailing the organisations involved in the bioeconomy and their interactions, as well as the processes and components involved in formulating bioeconomy strategies. Farmers are identified as key stakeholders in the bioeconomy (▶ Chap. 30), and ▶ Chap. 31 explores various approaches to sustainability management at farm level, including certification standards, digitalisation and collaborative efforts. ▶ Chapter 32 addresses the possibility of an innovation-triggered transformation towards a knowledge-based bioeconomy applying a Neo-Schumpeterian view that highlights the complex interplay in knowledge-generation and -diffusion processes between firms, consumers and government institutions. ▶ Chapter 33 further explores how inclusive innovation aims to improve the livelihoods of the most vulnerable by integrating their perspectives into innovation strategies. Inclusion, in this context, is viewed primarily as a process where multiple stakeholders provide input on the desirability of a specific innovation's design. Such inclusion is generally seen as essential for achieving societally desirable outcomes. Entrepreneurs play a crucial role in advancing the bioeconomy transition by acting upon entrepreneurial opportunities, often arising from market failures (▶ Chap. 34). Moreover, companies in the bioeconomy may adopt several approaches for sustainability management, including life-cycle assessment (LCA), certification, due diligence and traceability and supply chain models, all of which are described in ▶ Chap. 35. Consumers, too, significantly impact the development of the bioeconomy through their purchasing decisions. ▶ Chapter 36 examines the factors influencing consumer behaviour and the research methodologies used to analyse these factors, as well as strategies for managing consumer behaviour within the bioeconomy. The bioeconomy inherently addresses complex societal issues that involve multiple dimensions of conflict, necessitating a broad range of scientific and practical knowledge to devise solutions.

▶ Chapter 37 presents key definitions, principles and tools for conducting inter- and transdisciplinary research in the context of the bioeconomy. This part concludes with a reflection on the role of "the bioeconomist" in advancing the transition towards a sustainable bioeconomy. Along with a description of the bioeconomists competencies and profiles, this chapter also spotlights the education of a bioeconomist and its career pathways (▶ Chap. 38).

Part VI: Guiding the Bioeconomy Transition

Sustainability is a guiding principle of the bioeconomy. However, bioeconomy is not sustainable per se. The sixth part and last part of this textbook provides guidelines for the transition towards a future-oriented and sustainable bioeconomy. It begins by reflecting on the conditions for a responsible bioeconomy (▶ Chap. 39) yet also highlights how biodiversity and bioeconomy are interrelated and how the possible synergies and trade-offs between biodiversity and the bioeconomy can be described and understood in the context of the ecosystem services framework (▶ Chap. 40). ▶ Chapter 41 provides an in-depth overview of sustainability assessment methods in the bioeconomy, including environmental, economic and social assessment methods, describing how sustainability assessment results are ideally communicated and how sustainability assessment of bioeconomy systems are to be performed. ▶ Chapter 42 describes how the transition to a sustainable bioeconomy may be supported by modelling, scenario analysis and integrated model approaches, whereas ▶ Chap. 43 highlights how the results from bioeconomy monitoring are relevant for informing decision-making processes that shape the transition to a sustainable bioeconomy.

How to Use this Book

In order to facilitate a deeper understanding of the bioeconomy, each of the aforementioned sections is accompanied by interactive and supportive learning elements designed to enhance your learning journey. To maximise the benefits of your reading experience, we recommend familiarising yourself with the following brief sections, which provide an overview of the various features and resources this textbook offers.

- **Key Information at a Glance**
  At the beginning of every chapter, you will find an *abstract* and a list of *keywords*. The abstract offers a concise summary of the chapter's main points, giving you a quick overview of what to expect. The keywords highlight the essential concepts and terms covered in the chapter, ensuring you can easily refer to them as you study. We hope that this serves as helpful touchpoints, especially when revisiting a chapter for revision or exam preparation.
- **Structured Learning Path**
  To enhance your learning journey, each chapter begins with a short section containing carefully defined *learning objectives*. These objectives are your guide to what you should aim to learn by the end of

the chapter. They provide a roadmap, ensuring that you focus on the most important aspects as you work through the material. Refer to these goals before and after reading to track your progress and assess your learning journey.

- **Didactic Elements for In-Depth Understanding**
  To enhance your learning, we integrated various didactic elements throughout the book. These will help reinforce your comprehension and ensure you fully grasp the subject matter of each chapter. Therefore, you will not only find key *definitions* that highlight important terms and concepts but also *examples* that illustrate how these terms and concepts are realised in real-world contexts, allowing you to see their practical application. For a deeper dive into specific topics, we included numerous *excursus* elements. These offer additional insights or related information that enriches your understanding of the main text. Additional questions for reflection, tips for further reading as well as exercises to deepen your understanding of some of the contents are included in *Food for Thought* boxes. Aim to read through them to improve your understanding and to contextualise what you have read based on your own experiences and understandings.
- **Visual Learning Support**
  As reading through multiple chapters to find the information you are looking for can be straining, we included a video summary at the beginning of each chapter. Presented with the help of our virtual student ambassadors, these summaries should serve as a helpful introduction, providing a visual summary of each chapter's main topics. Watching these videos will hence give you an initial understanding of the material, making it easier to navigate the more detailed content that follows. Feel free to revisit the video after reading to reinforce your understanding or clarify any remaining questions. For some chapters, you will also find additional videos, some of which are taken from our *Massive Open Online Course (MOOC) "Concepts of Sustainable Bioeconomy"* that complements the content of this book, others which have been specifically designed to improve your understanding of a certain concept or topic. While our specifically designed videos as well as our video summaries will be directly accessible throughout the book, you may access the videos taken from our MOOC through the supplementary material as well as on a separate course platform free of charge. To access the online course platform, follow the instructions below:
  1. Use the link ▶ sn.pub/m03wci to access the online course.
  2. For first-time use, please register on the learning platform first.
- **Active Learning Through Questions & Answers**
  To ensure that you can apply what you have learned, each chapter concludes with a *Questions & Answers* section. These questions are designed to test your comprehension and encourage reflection on the key points covered. Answering these questions will help you consolidate your knowledge, and in case of difficulty, the corre-

sponding answers will provide you with additional explanations, clarifications and alternative perspectives. For students, working with this section is advised, as one or another question may end up as an exam question.

- **Learning at Your Own Pace**
  When we designed this book, one of our main goals was for it to allow for flexible learning. While the individual parts and chapters guide you through different aspects of the bioeconomy, feel free to engage with the content at your own pace. You might prefer to skim through the video summary first, then read the main text or perhaps focus on the questions before diving into the content. The key is to approach the material in the way that best suits your learning style and objectives.
  By combining all these resources, you can engage with the book in a comprehensive, active and meaningful way. Make sure to leverage these features to deepen your understanding and apply what you have learned effectively.

We hope this book provides you with valuable insights and a rewarding reading experience!

Yours truly,
The Editor Team

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Bioeconomy Context, Concepts, and Principles

The first part of the textbook addresses the context in which the bioeconomy operates and its role in contributing solutions to global challenges. It explains the concepts of the bioeconomy and its underlying principles, including sustainability, multidimensionality, multifunctionality, circularity, cascading resource use, inter- and transdisciplinarity, and a holistic systems thinking approach. Finally, it describes bio-based value chains and webs as the basis of bioeconomy systems.

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Context

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Fig. 1.0 The context of the bioeconomy (▶ https://doi.org/10.1007/000-htb)

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The future bioeconomy is expected to drive the transition toward a more sustainable economy by addressing some of the major global challenges, including securing food security, climate change, environmental degradation and resource scarcity. The globally increasing demand for food, but also materials and renewable energy, necessitates innovative developments in the primary sectors. Innovations will need to generate more resource-use efficient technologies and methods for increasing productivity in agriculture, forestry and aquaculture without jeopardizing the Earth's carrying capacity and biodiversity. Bioeconomy exploits new resources by building on renewable biomass. Through this, the introduction of innovative and resource-use efficient production technologies and the transition to a sustainable society, it helps to substitute or reduce the use of limited fossil resources, thereby contributing to climate change mitigation.

Learning Objectives

After studying this section, you will…

- …be able to describe the main challenges of the twenty-first century (see ► Sects. 1.1, 1.3, and 1.4)
- …be able to describe the interrelations between the causes of these challenges (see ► Sect. 1.3)
- …be able to explain how bioeconomy can contribute to meeting these challenges (see ► Sect. 1.5)

Over the course of 1 year, the Earth travels 940 million km around the sun, from which it receives 1366 W/m^2 of solar radiation (2,500,000 EJ per year). Of this, 0.25% is transformed into usable biomass through the process of photosynthesis. The Earth's vegetation sequesters about 175 petagrams (175,000,000,000,000 kilograms) of carbon a year, equivalent to about 300,000 billion tons of biomass (Welp et al. 2011). Carbon is the most important element of our economy, which may be called a carbon economy, given that carbon is the main building block of most chemical compounds that we produce and consume. Before humankind discovered fossil oil, coal, gas and uranium and learnt how to put them into use, biomass covered all human needs for food, energy and materials.

1.1 Fossil Resources and Climate Change

The use of fossil resources fueled industrialization, which was driven by technical and economic processes causing a shift from mainly agrarian toward industrial production. However, the availability of fossil resources is limited, and its increased use resulted in negative environmental effects. Today, there are an estimated 42,268 EJ of fossil energy reserves and 496,952 EJ of fossil energy resources spread across the globe (see ◘ Fig. 1.1, BGR 2023). *Reserves* are the amounts of energy sources that have been determined with high accuracy and are economically exploitable, whereas *resources* are the amounts of an energy resource for which there is geological evidence, but which are either economically or geologically not exploitable. Currently, fossil energy reserves exceed the global primary energy consumption of 620 EJ 68 times. However, crude oil, which is also required for material uses, makes up only 25% of fossil reserves (BGR 2023) and is therefore expected to be the first fossil resource to deplete.

Fossil resources include coal, petroleum, natural gas, oil shales, bitumen, tar sands, and heavy oils. All contain carbon and were formed as a result of geologic processes acting on the remains of organic matter produced by photosynthesis (see ► Sect. 5.2). These processes began in the Archean Eon more than 3 billion years ago. Most carbonaceous material occurring before the Devonian Period (approximately 415 million years ago) was derived from algae and bacteria (Kopp 2024).

Fossil resources were formed from biomass through geological processes that

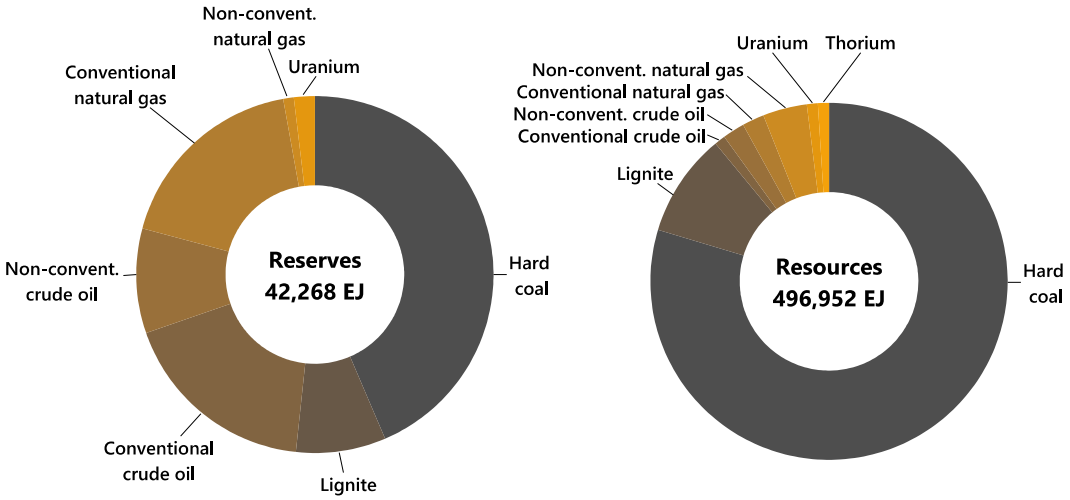


Fig. 1.1 Reserves and resources of fossil resources (BGR 2023)

Table 1.1 Carbon contents of fossil resources and amounts of carbon dioxide (CO_2) and other greenhouse gases (GHG) when fossil fuels are used energetically

Fossil resource	% Carbon (C)[a]	Greenhouse gas emission [t/t][b]		
		CO_2	N_2O	CH_4
Hard Coal	71.6	2.6	0.000027	0.000040
Lignite	32.8	1.2	0.000012	0.000018
Petroleum	84.8	3.1	0.000127	0.000025
Natural gas	73.4	2.7	0.000048	0.000005

[a] IPCC (2006)
[b]Own Calculation based on IPCC (2006)

occurred several million to billion years ago. For this reason, they have a high carbon content (see Table 1.1). With every ton of fossil oil or coal burnt and transformed to energy, about 0.8 tons of carbon are oxidized and 3 tons of carbon dioxide (CO_2) are released into the atmosphere (see Table 1.1).

The atmospheric concentrations of the major greenhouse gases (GHG) carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have shown increases of 47%, 156% and 23%, respectively, since the year 1750 (IPCC 2023). These increases are mainly driven by the combustion of fossil fuels, deforestation, and soil-borne greenhouse gas emissions. In 2019, global net anthropogenic GHG emissions have been estimated to be 59 ± 6.6 GtCO2-eq approximately, with 34% (20 Gt CO_2-equivalents) of net global GHG emissions coming from the energy sector, 24% (14 Gt CO_2-equivalents) from industry, 22% (13 Gt CO_2-equivalents) from AFOLU (agriculture, forestry, land use change), 15% (8.7 Gt CO_2-equivalents) from transport and 6% (3.3 Gt CO_2-equivalents) from buildings (IPCC 2023). Today, electricity and heat production, industry, and land use-related activities are the sectors that contribute most to the so-called "global warming potential (GWP)," which is expressed in CO_2-equivalents (see Fig. 1.2). CO_2-equivalents include the weighted effect of CO_2 ($GWP_{100\ yr} = 1$), CH_4

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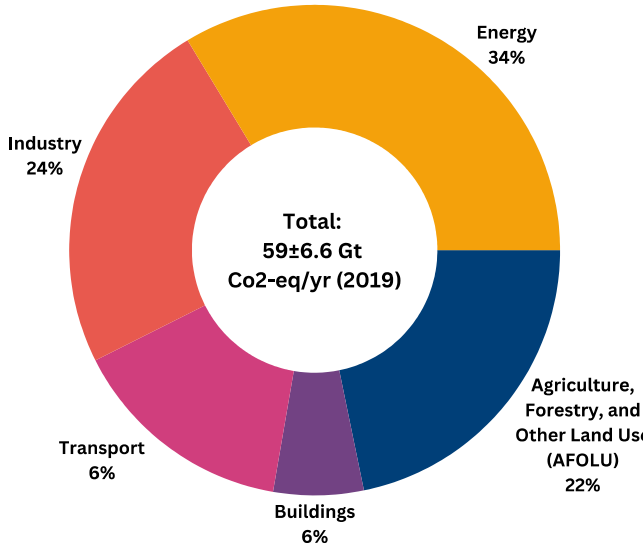


Fig. 1.2 Total anthropogenic greenhouse gas (GHG) emissions (gigatons of CO_2- equivalent per year, $GtCO_2$-eq/yr) from economic sectors in 2019. (Based on IPCC 2023)

($GWP_{100\,yr}$ = 28) and N_2O ($GWP_{100\,yr}$ = 265) on global temperature. The higher the $GWP_{100\,yr}$, the more a molecule of a GHG contributes to global warming and climate change over 100 years.

Greenhouse gases (GHGs) in the atmosphere lead to the so-called *greenhouse effect*. The Earth's surface absorbs some of the energy from sunlight and heats up. It cools down again by giving off this energy in a different form, called infrared radiation. This infrared radiation escapes back to space but, on the way, some of it is absorbed by GHGs in the atmosphere, thus leading to a net warming of the Earth's surface and lower atmosphere (see Fig. 1.3).

The direct and indirect effects of the increasing atmospheric concentration of GHGs and concomitant increasing global temperatures are manifold and include (IPCC 2014):

- Ocean warming and acidification (through uptake of CO_2)
- Melting of the Greenland and Arctic ice sheets
- Sea level rise (1.5–1.9 mm/year), threatening ► coastal communities and ecosystems
- Glacial retreat
- Decreased snow cover and increased permafrost temperatures
- Reduction in precipitation and increased occurrence of drought, especially in areas already critically affected by water limitation
- Extreme and unpredictable weather events such as storms and flooding
- Anticipated negative temperature, drought and other (e.g., diseases) impacts on agriculture, potentially leading to yield losses.
- Negative impact on human health through deteriorating air and water quality, increasing the spread of certain diseases, and altering the frequency or intensity of extreme weather events.

The IPCC (International Panel of Climate Change) formulated a "climate goal" of 2 °C—the increase in global temperature that should not be exceeded in order to avoid disastrous global effects. To ensure CO_2-induced warming remains below 2 °C would require cumulative CO_2 emissions from all anthropogenic sources to remain below about 3650 $GtCO_2$ (1000 GtC); over half this amount had already been emitted by 2011 (IPCC 2014). One high potential GHG mitigation option is the use of bio-based instead of fossil resources.

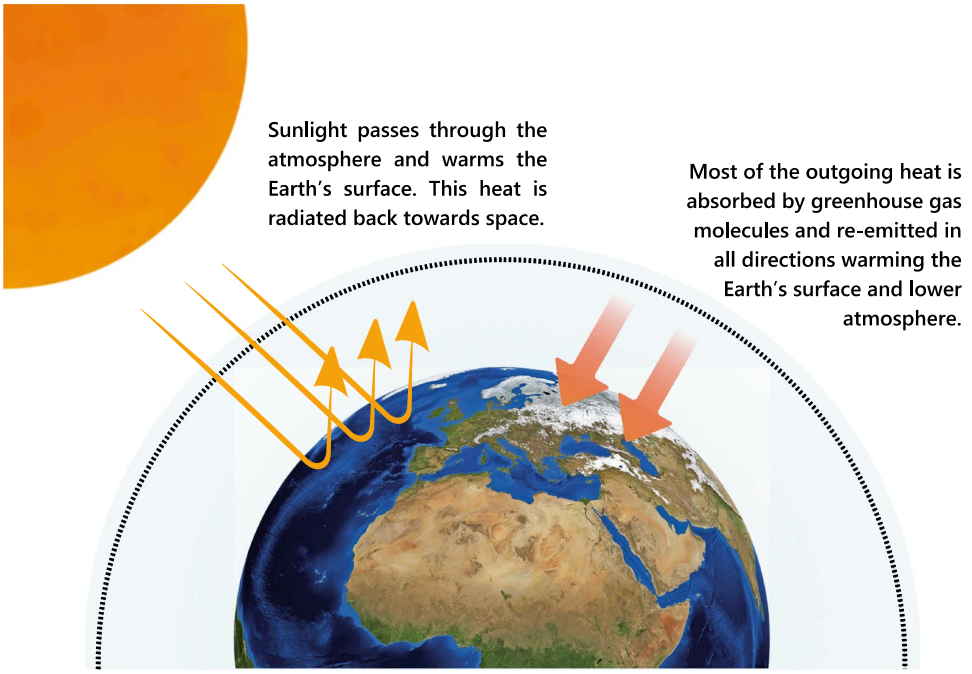


Fig. 1.3 How greenhouse gases lead to global warming. (According to National Aeronautics and Space Administration 2024)

1.2 Bio-based Resources

The resources produced and used in a bio-based economy all contain carbon (C). Therefore, they are suitable to replace carbon-based fossil resources, that is, coal, oil, and natural gas. In the following chapters, bio-based resources are defined as all renewable resources containing non-fossil, organic carbon, recently (<100 years) derived from living plants, animals, algae, microorganisms or organic waste streams (see ▶ Chap. 5 for a more detailed description of bio-based resources).

> ***Bio-based resources*** are of biological origin and stem from biomass. This biomass can be untreated or may have undergone physical, chemical, or biological treatment.

> ***Biomass*** stems from living or once-living organisms, including plants, trees, algae, marine organisms, microorganisms, and animals. Excluded are materials embedded in geological formations and/or fossilized.

Both bio-based and fossil resources are derived from biomass that has been built through the process of photosynthesis (see ▶ Sect. 5.2). During that process, CO_2 is taken up by plants or algae with the help of light energy. Plants and algae convert light to chemical energy by integrating carbon (C) into their organisms. The carbon bound in fossil fuels was thus taken up from atmospheric CO_2 several million or billion years ago. By contrast, bio-based resources are composed of recently grown biomass where there is a short time span of 1 to <100 years between the withdrawal of CO_2 from the atmosphere and its release back into the atmosphere. Therefore, biomass is often considered "CO_2 neutral" and "renewable" because the same amount of CO_2 is bound and then released again within a short period of time.

With an annual increment of 300,000 billion tons of biomass, bio-based resources form a very large and, because they grow back, theoretically unlimited resource. However, their production necessitates the use of natural resources, mainly land, soil, water, and plant nutrients.

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Excursus 1.1: Renewable Carbon Economy

The principle of renewable carbon is based on the circumstance that climate change is not fundamentally a "CO_2 problem" but rather an issue of excessive fossil carbon entering the atmosphere. This fossil carbon, extracted from crude oil, natural gas, and coal, disrupts the carbon balance by adding "new" carbon (in the form of CO_2) into the atmosphere that would otherwise remain underground. If this inflow of fossil carbon were halted, atmospheric CO_2 levels would stabilize since CO_2 can be cycled naturally between the atmosphere, biosphere, and technosphere (von Berg et al. 2023).

Biomass and the Bioeconomy are an important part of the renewable carbon economy besides recycling and carbon capture technologies.

Natural resources occur naturally on the Earth. They include (a) biotic resources, stemming from living organisms (mainly plants and animals) and organic material (also fossilized) and (b) abiotic resources from non-living and inorganic material, such as air, soil, water, sunlight, and minerals.

1.3 Planetary Boundaries and Limitation of Natural Resources: Current Status

Planetary boundaries define the limits within which humanity can operate safely without destabilizing Earth's systems. An economy based on renewable carbon (e.g. biomass) offers a pathway to address socio-economic

Excursus 1.2: The Nine Planetary Boundaries

1. *Stratospheric ozone depletion*: The ozone layer in the stratosphere protects all living creatures from dangerous ultraviolet radiation. The thinning of the ozone layer in the upper atmosphere, primarily due to human-made chemicals (e.g., Chlorofluorocarbons (CFCs)), allows more harmful UV radiation to reach Earth's surface.
2. *Loss of biosphere integrity* (biodiversity loss and extinctions): Biodiversity and the intactness of ecosystems stabilze the entire earth system. Human intervention in nature threatens this ecological stability (e.g., through destruction of ecosystems and the extinction of species).
3. *Release of novel entities* (formerly called chemical pollution): Introduction of new substances into the environment that did not exist before. Examples are chemicals such as persistent organic pollutants (POPs) and persistent, bioaccumulative and toxic chemicals (PBTs), or microplastics and colorants.
4. *Climate change*: The change in the ratio of incoming and outgoing energy of the Earth, caused by increased greenhouse gases (like CO_2) and aerosols. Normally, the Earth absorbs radiation and sends some of it back into space. Greenhouse gases and aerosols act like a blanket, holding the heat in. As more of these gases build up, more radiation gets trapped and causes an increase in global temperatures and alters climate patterns.
5. *Ocean acidification*: Ocean acidification is the phenomenon of increasing acidity (decreasing pH) in ocean water. The reason for this is the increasing amount of CO2 in the atmosphere, which is absorbed by the water and turns into carbonic acid. This process harms calcifying organisms, impacting marine ecosystems, and reduces the ocean's efficiency in acting as a carbon sink.
6. Freshwater consumption and the global hydrological cycle: Availability of fresh water for humans, plants and other living organisms. The alteration of freshwater cycles, including rivers and soil moisture, impacts natural functions such as carbon sequestration and biodiversity, and can lead to shifts in precipitation levels.

7. Land-system change: The transformation of natural landscapes, e.g. through deforestation and urbanization, diminishes ecosystems and their functions like habitats for wildlife, moisture recycling and carbon sequestration.
8. Modification of biogeochemical flows: Nitrogen and phosphorus, which are crucial for supporting life and maintaining ecosystems, move in cycles and in quantities that ecosystems have adapted to during evolution. These cycles are disrupted trough anthropogenic activities (e.g., industrial fixation and usage of nitrogen as fertilizer).
9. Atmospheric aerosol loading: The rise in airborne particles (e.g. emissions from aerosols) from human activities or natural sources influences the climate by altering temperature and precipitation patterns and have a negative impact on human health. (Stockholm Resilience Center 2023)

challenges, such as climate change and resource scarcity, while aligning with these boundaries.

» "The planetary boundaries concept presents a set of nine planetary boundaries within which humanity can continue to develop and thrive for generations to come" (Stockholm Resilience Center 2023).

Climate change is one of the nine planetary boundaries (see Fig. 1.4) that the UN has characterized as demarcating the carrying capacity of the Earth and the vulnerability of global natural resources (Steffen et al. 2015). According to these, climate change and land-system change processes as well as biosphere integrity (in particular genetic diversity) and biogeochemical flows (specifically nitrogen and phosphorus flows to the biosphere and oceans as a result of various industrial and agricultural processes) were already beyond the safe operating space in 2015. Since then, also freshwater consumption and the global hydrological cycle as well as the release of novel entities have exceeded the boundary and entered the red space (see Fig. 1.4).

Biodiversity integrity describes "the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat of the region" (Karr and Dudley 1981, p 56). It therefore has a functional as well as a quantitative (number of species and individuals) component (Angermeier and Karr 1994).

Agriculture, the primary source of food and feed and an important sector in the bioeconomy, has been responsible for significant biodiversity losses. Aside of deforestation and other land use changes converting areas of high biodiversity value into agricultural land, the key drivers of the decline in biodiversity and in conservation and ecosystem services are the increased utilization of pesticides, herbicides and fertilizers, increased landscape homogeneity associated with regional and farm-level specialization, drainage of waterlogged fields, loss of marginal and un-cropped habitat patches, and reduced fallow periods (Hilger et al. 2015; Lambin et al. 2001). The current high rates of ecosystem damage and extinction can be slowed by efforts to protect the integrity of living systems (the biosphere), enhancing habitat and improving connectivity between ecosystems while maintaining the high agricultural productivity that humanity requires (Steffen et al. 2015).

Other natural resources necessary for agricultural production are also under threat. While the production of agricultural goods has increased 2.5 to 3 times since the year 1961, the agricultural land area has only expanded by 12% (FAO 2011). Because more than 40% of the increase in food production stems from irrigated areas, water use has also increased. Today, 70% of all water withdrawn

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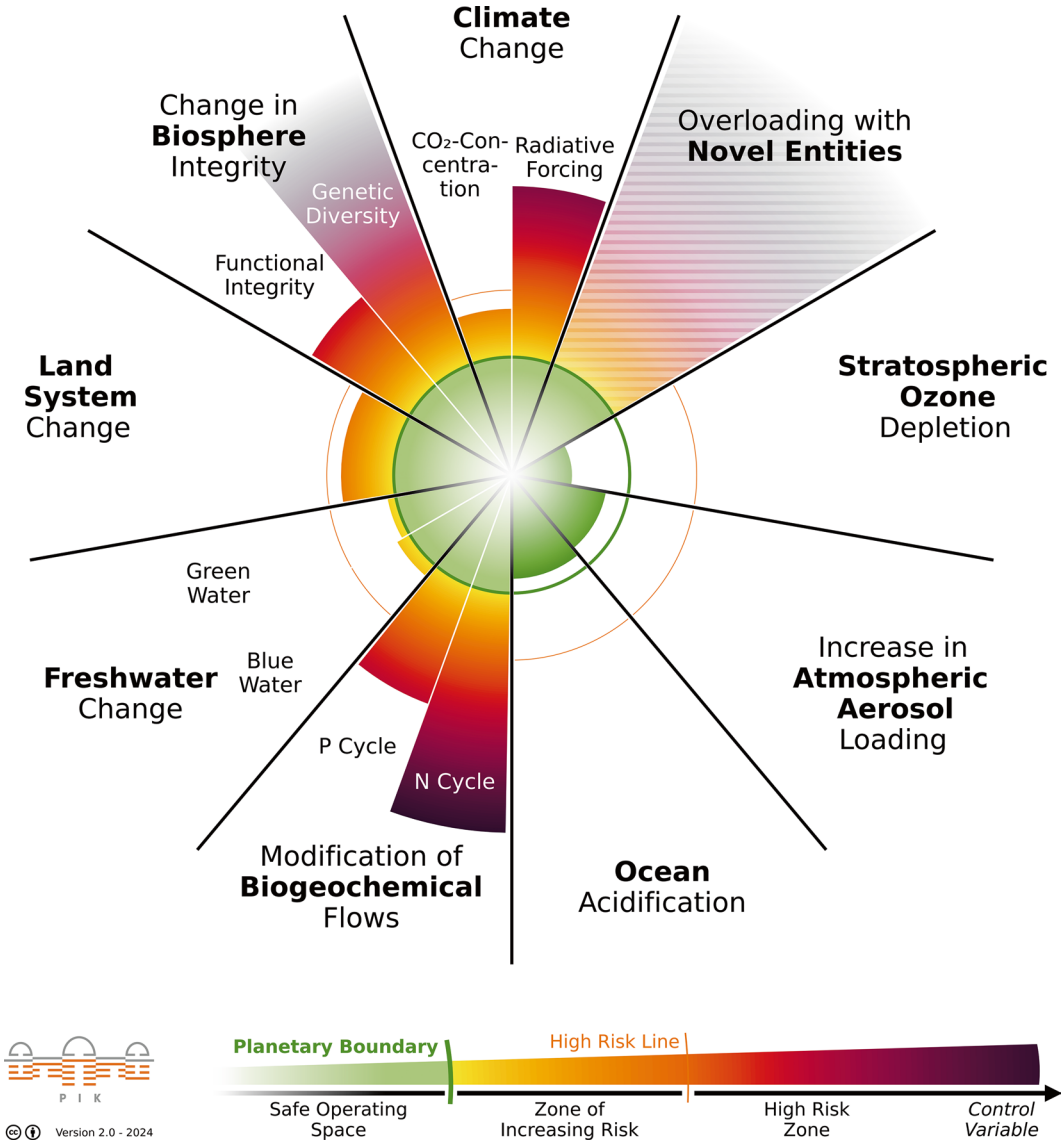


Fig. 1.4 The nine planetary boundaries, update for 2024. The green-shaded area represents the safe operating space. (From Potsdam Institute for Climate Impact Research (PIK), licensed under CC BY 4.0)

from aquifers, streams, and lakes is used for agricultural production, leading to water scarcity in many areas of Asia, northern and southern Africa, and western North America (FAO 2011). Intensive agricultural use and deforestation have also led to soil degradation processes, such as erosion. Very degraded soils are found especially in semi-arid areas (Sub-Saharan Africa, Chile), areas with high population pressure (China, Mexico, and India), and regions undergoing deforestation (Indonesia) (UNEP 1997). Finally, the plant nutrient phosphorus (P) is also expected to become a limited natural resource for crop production. Phosphate fertilizer used in agriculture is mainly produced from rock phosphate (RP). However, RP is a finite resource, as with all mined resources. For this reason, in 2014, the EC added it to the list of critical raw materials (EC 2014).

In an update of the planetary boundaries framework in 2023, transgression in six plane-

tary boundaries was reported—biogeochemical flows, freshwater change, land system change, biosphere integrity, climate change, and novel entities, indicating that we are currently beyond the "safe operating zone" (Richardson et al. 2023). The status of planetary boundaries indicates an urgent need for action at all levels, and for the bioeconomy they imply the "safe" limits for it to be implemented, without further creating pressure on those boundaries that lead to increased risks but rather contributing to mitigate the transgression.

Because bioeconomy makes direct use of natural resources (especially soil, land, water, and nutrients) and therefore depends on their availability, it is at the focus of the sustainability debate. Only a bioeconomy that makes responsible use of natural resources, including their efficient use, conservation, restoration, regeneration, and recycling, can contribute to the transformation to a more sustainable economy. For this process, the bioeconomy will have to drive innovations further toward sustainable agricultural intensification. This is defined as "producing more output from the same area of land while reducing the negative environmental impacts and at the same time increasing contributions to natural capital and the flow of environmental services" (Pretty et al. 2011). Sustainable agricultural intensification necessitates the use of innovative methods to produce modern varieties, fertilizers and crop protection measures (see ▶ Sect. 6.11). This aspiration is in line with recent trends, which show that about 70% of total factor productivity in agriculture is derived from innovations and only about 12% from land area extension. Also, other sectors producing biomass, such as forestry and aquaculture, need to apply sustainable production methods (see ▶ Chaps. 8 and 9).

A sustainable bioeconomy is not yet reached when fossil resources have been substituted by bio-based resources to the maximal possible extend. It also requires that the replacement of fossil fuels by bio-based resources results in an overall more sustainable economy. To ensure this, in the bioeconomy principles such as systems and life-cycle thinking (see ▶ Chap. 3) are applied. Tools for sustainability assessment, such as Life-cycle Assessment (LCA), are developed (see ▶ Chap. 41). At process level, management options, such as good practices or certification, support the operationalization of sustainable bio-based value chains (see ▶ Chaps. 31 and 35).

1.4 Population Growth and Food Security

It is projected that the world's population will increase from the current 7 billion people to 9.7 billion in 2050 (FAO 2021). Today (2020), almost 768 million people are undernourished, particularly in Sub-Saharan Africa and Asia (FAO 2021). In addition to the demands of the growing population, economic development, especially in the emerging economies, leads to increasing consumption of meat. That means the trend toward increasing meat consumption in the emerging economies of Africa and Asia, and the concomitant increase in global meat production will continue (see ◘ Fig. 1.5). It is estimated that by 2050 an extra billion tons of cereals and 200 million tons of livestock products will need to be produced annually (Bruinsma 2009). However, meat production requires more land than crop production. To produce one kilogram (kg) of meat, 3–100 kg of biomass are required, depending on which animals and production systems are used (Smeets et al. 2007). FAO estimates that agricultural production will have to produce almost 50 percent more food, livestock fodder and biofuel than in 2012 to satisfy global demand and to achieve "zero hunger" by 2030 (FAO 2021). A shift to plant-based food (▶ Chap. 21) could release the pressure. According to a report of UNEP, plant-based protein products would require up to 97 percent less land and 30–50 percent less energy to produce compared to conventional beef, pork, or chicken production. Additionally, up to 90% less GHG emissions would arise (UNEP 2023).

In food production, quantity is not the only criterion; quality is also important. One of the first quality management steps in the bio-based value chain is the protection of crop and animal health. This is aimed not

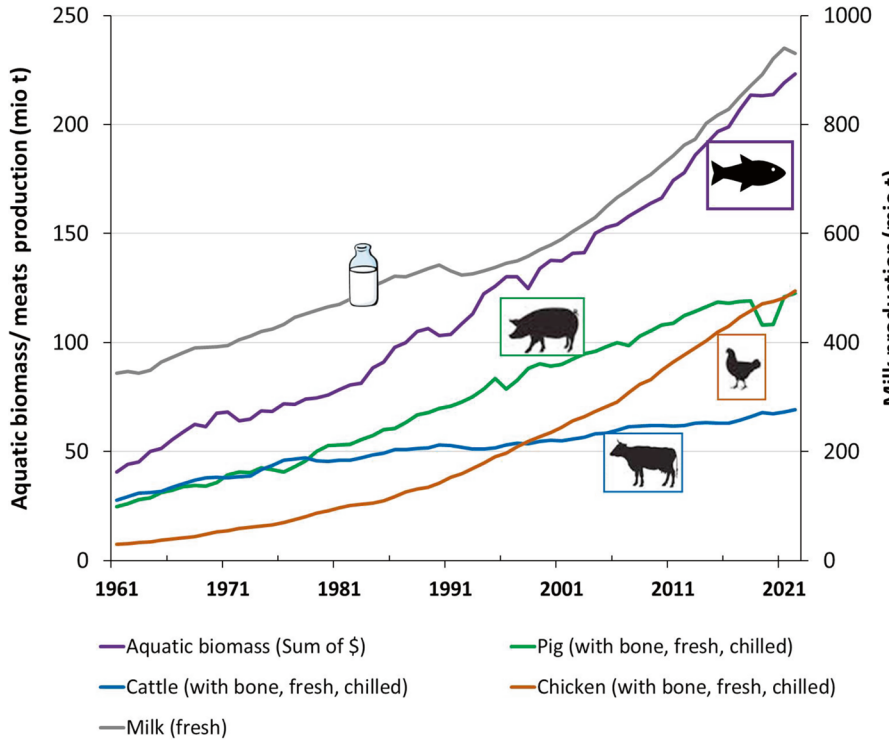


Fig. 1.5 Global production of aquatic biomass[($)] from capture fishery and aquaculture, fresh meats and milk in 1961 to 2022 based on FAO (2024a, b); [($)] refers to: aquatic plants, seaweed and algae; aquaculture (freshwater, marine, & brackish waters); capture fishery (inland & marine waters)

only at delivering good quality foodstuffs, but also at increasing productivity and reducing losses in the production, storage, transport and processing of biomass. Even before food discarded at consumer level is considered, food losses along the supply chain are estimated to be as high as 35% for cereals and more than 50% for perishable products such as roots, tubers, fruits and vegetables (Aulakh and Regmi 2013). Avoiding such losses requires disease-resistant varieties, effective crop protection measures and better training of farmers to apply these technologies, infrastructure for storage and transportation, and efficient processing and conversion methods (see ▶ Chap. 6).

The transition to a knowledge-based bioeconomy also depends on consumers being aware of the nature and characteristics of bio-based products (see ▶ Chap. 36). Otherwise, they will neither be able to identify more sustainably produced products, nor will they be willing to pay a higher price for higher-value products. The process of raising awareness will also result in a more conscious choice of higher-quality, healthier products with a lower environmental impact, and could also result in a reduction in meat consumption.

The availability of sufficient high-quality food for a growing population is thus not only a matter of sufficient production but also a matter of appropriate use and food consumption patterns. Finally, also the question of fair food distribution and adequate access of all people to food determines food security. Also, today's hunger is not caused by insufficient global food production but by politically driven distribution problems.

Do you want to learn more about bioeconomy and food security? Take a look at Supplementary Video 1.1, a video from our MOOC "Concepts of Sustainable Bioeconomy" (2021).

1.5 The Role of the Bioeconomy in the Face of Global Challenges, Wicked Problems, and the Sustainability Transformation

The aim of this textbook is to illustrate opportunities that the bioeconomy offers to contribute to addressing global challenges by means of integrated innovations at technological, institutional and social levels that can lead to a societal transformation. The bioeconomy stands for:

- **Provision of renewable resources—food, feed, fiber, fuel, fun:** As non-renewable fossil resources are finite and generate significant ecological externalities (e.g. climate-change impact), we need to meet our demands for food, products, and materials as well as energy through renewable resources. Foodstuffs and renewable materials are mainly supplied through biomass from agricultural production, forestry, and aquaculture (▶ Chapts. 6, 8, and 9). But renewable energy, to which bioenergy (▶ Chap. 24) presently contributes 73% (with biomass covering approximately 14% of the global final energy consumption (REN21 2016), can also be supplied through solar, wind, geothermal, hydro or tidal energy.
- **Sustainable land use:** Given that land use presently contributes 22% of anthropogenic GHG emissions and to a large share of biodiversity losses, agricultural and forestry land-use management needs to be improved in a sustainable way. The bioeconomy provides nature-based solutions (see ▶ Sect. 5.5), for example, climate-smart production methods that make use of soil carbon sequestration and innovative agricultural technologies that reduce emissions and ecological impacts (see ▶ Sect. 6.11). These result in GHG mitigation and are often associated with improved efficiencies, lower costs, and environmental co-benefits (Smith et al. 2007).
- **Circularity and sustainability:** The bioeconomy can address global challenges only if it is circular and sustainable. This means that nutrient and material cycles are closed and all bio-based resources are allocated regarding achieving the maximal ecological, social and economic benefit (see ▶ Chap. 3). This holistic approach in resource allocation represents a major pillar of a circular sustainable bioeconomy and may serve as a blueprint for resource allocation strategies in general.
- **Life cycle thinking and value chain approach:** Bioeconomy goes far beyond the idea of building a bio-based economy. It also builds on sustainable development through the application of biological and system knowledge and the generation of innovations for developing a sustainable economy. This is not a sectoral approach in which only the economic activities that are using bio-based resources are considered. Life cycle thinking (see ▶ Chaps. 3 and 41) and value chain approaches (▶ Chap. 4), resource use efficiency and recycling concepts are applicable to all production activities. Therefore, bioeconomy is an integrated and forwardly approach that can serve as a blueprint for an overall economic system development toward sustainability.
- **Research, development and innovation:** The global demand for more and higher quality food and the limited availability of land and natural resources necessitates a thrust on innovation (see ▶ Chap. 32) in agricultural, forestry, aquaculture, and other forms of biomass production as well as biomass processing and use. This must result in more efficient and less resource-consuming production methods along bio-based value chains (see ▶ Chap. 4). Through a knowledge-based approach, more efficient and sustainable production methods must be applied in order to manage natural resources sustainably and increase productivity. Complementary to technological advances, new forms of organizing societal actors, business models, and institutional innovations are key to foster transformation processes and ensure a system change.
- **Stakeholder-orientation:** The limited, and in part already overstretched, planetary

1

boundaries make a shift to a more sustainable economy imperative, which makes better and responsible use of the Earth's resources. The change to a sustainable economy requires sustainability-conscious producers and consumers who steer economic activities through their businesses, capabilities, targeted preferences, and choices. Bioeconomy has become the guiding concept for large areas of economic development and the urgently needed societal transition to achieve this goal.

- **Normative direction:** The societal transition in the bioeconomy is led by awareness raising, not only for the global challenges we face but also for ways to deal with them. For instance, the *food-first principle* provides that global food security is given priority over all other pathways for utilising bio-based resources. This should ensure that the demand for high quality food is satisfied for all people (Priefer et al. 2017). In the recent years, such normative aspects of the bioeconomy have gained importance involving different stakeholders and making them aware of their responsibility but also of ethical conditions for the success of the sustainability transformation. Alongside, stakeholders are also made aware of the need of sufficiency approaches (see ▶ Sect. 3.1) to reduce the resource consumption as well of innovative and potentially more resource use efficient ways toward fulfilling demands.
- **Rural development:** The ubiquitous nature of biomass offers the possibility of creating modern jobs in rural areas, thus counteracting both the limited geographical distribution of accessible fossil resources and the current concentration of job and income opportunities in urban areas. The bioeconomy aims to enable areas rich in bio-based resources to improve income and development opportunities. The development of innovative technologies will also generate new jobs with a modern profile (e.g., digitalization, see ▶ Chaps. 15 and 25).
- **Providing answers to wicked problems:** Tackling several or even all global challenges simultaneously is a complex issue due to the many trade-offs and interdependencies amongst them. This can be seen in the task of simultaneous need for production activities to provide food and consumables and climate change mitigation. Through the use of nature-based solutions and application of principles of circularity and multi-functionality (see ▶ Chap. 3), the bioeconomy provides operational approaches to best manage these trade-offs. Concrete examples are the integrated approach of producing ecosystem services (see ▶ Sect. 6.11 and ▶ Chap. 40)—including biomass production as well as ecological functions such as carbon sequestration—as well as biorefineries (see ▶ Chap. 17) making full use of the biomass resource potential for the provision of food, feed, materials and energy.
- **Informed decision-making:** In the bioeconomy, resource supply must be sustainable and therefore the use of bio-based resources should only be implemented when they perform more sustainable than the fossil alternative. For a sustainable bioeconomy, tools for the assessment and management of sustainability, such as life-cycle assessment (see ▶ Chap. 41) have been developed and meanwhile their application reaches beyond bio-based value chains.
- **Transformative skills and knowledge:** The sustainability transformation needs political support (see ▶ Chaps. 2, 28, and 29), stakeholder involvement (see Part V) and information that can be provided through modelling (see ▶ Chap. 42) and bioeconomy monitoring (see ▶ Chap. 43). The implementation of the transformation requires experts with a system's understanding and the ability to deal with complex, so-called wicked problems. Wicked problems differ from tame problems in that they cannot be addressed using the linear logic of conventional rationality or understood through quantitative and objective information alone (see ▶ Sect. 38.1). Alongside the global growth of the bioeconomy, the need for experts as well as educational programs that are able to educate and train these experts is steadily

increasing. Such programs have to enable experts to take collective action across societal sectors to generate impactful, transformative change of organizations and systems, to acquire the required inter- and transdisciplinary knowledge (see ▶ Chap. 37) and to adopt the collaborative and transformative skills needed to support the sustainability transformation (see ▶ Chap. 38).

The bioeconomy can contribute to address global challenges through its nature as an economy building on renewable resources, biological knowledge, innovation, and knowledge generation, and through holistic approaches that think along value chains and in value webs. This means that bioeconomy does more than just follow traditional pathways of biomass production, conversion, and use. It leads the way toward an innovative and sustainable use of the Earth's limited resources and provides the guidelines for the societal transition toward sustainable development.

Do you want to learn more about the importance of the bioeconomy? Take a look at ◘ Supplementary Videos 1.2 and 1.3, videos from our MOOC "Concepts of Sustainable Bioeconomy" (2021) that explain the context of the bioeconomy in more detail.

Questions

1. What are the consequences, advantages, and disadvantages of the use of fossil resources?
2. How can the use of bio-based resources overcome the shortcomings of fossil resources?
3. How can the production of bio-based resources help to keep the carrying capacity of the Earth within the planetary boundaries or, where they have already been exceeded, to fall back to within the boundaries?
4. What are the potential contributions of the bioeconomy to meeting major global challenges?
5. What are the conditions for a sustainable bioeconomy?

Answers

1. Fossil fuels, such as coal, oil, and natural gas, have powered industrialization and modern economies due to their high energy density and reliability. They are widely available and supported by established infrastructure, making them economically viable. However, their use has severe environmental and social consequences. Burning fossil fuels is the largest source of greenhouse gas emissions, driving climate change and global warming. Extraction processes damage ecosystems, while air and water pollution harm human health. Fossil fuels are finite, raising concerns about long-term energy security. Their geopolitical importance also fuels conflicts over resource control. While fossil fuels have enabled technological progress, their drawbacks—environmental degradation, finite supply, and contribution to global warming—underscore the need for a transition to renewable energy. Sustainable alternatives can balance energy needs with environmental protection and long-term economic stability.
2. The use of bio-based resources can address many shortcomings of fossil resources. Derived from renewable materials like plants, algae, and waste, bio-based resources reduce dependency on finite fossil fuels. Their renewable nature ensures a consistent supply, improving long-term resource supply security. When bio-based resources substitute fossil resources, they reduce greenhouse gas emissions, helping combat climate change, and can be biodegradable, reducing pollution. The ubiquitous nature of biomass offers the possibility of creating modern jobs in rural areas, thus counteracting both the limited geographical distribution of accessible fossil resources and the current concentration of job and income opportunities in urban areas.
3. The production and use of bio-based resources can help maintain Earth's car-

rying capacity within planetary boundaries by reducing environmental pressures. Unlike fossil resources, bio-based materials are renewable and can be produced sustainably, lowering greenhouse gas emissions and mitigating climate change. They support carbon neutrality by capturing CO_2 during biomass growth, balancing emissions from their use. Sustainable bio-based production can prevent biodiversity loss by promoting sustainable and ecologically sound farming and forestry practices. In bioeconomy, the production of bio-based resources is combined with the provision of ecosystem services, such as carbon sequestration, by applying nature-based solutions. These can, together with the application of technologies that enhance efficiency in agricultural production, reduce the emissions of nitrogen and phosphorus into the environment, reduce water demand, and help to regenerate the natural resources, such as soil and water.

4. The bioeconomy can significantly address major global challenges by promoting sustainable development and environmental protection. It supports food security through sustainable agricultural practices and providing innovations that help sustainable intensification, which according to Pretty (2011) means "producing more output from the same area of land while reducing the negative environmental impacts and at the same time increasing contributions to natural capital and the flow of environmental services." Sustainable intensification approaches lead to more efficient resource use, are minimizing wastes and losses in food production and apply practices for reducing environmental degradation and enhancing regenerating. The bioeconomy leverages renewable biological resources to produce materials, products and energy, reducing reliance on fossil fuels and mitigating climate change. By advancing renewable energy and biodegradable materials, the bioeconomy helps combat pollution and preserve ecosystems. The bioeconomy also fosters economic growth and job creation by driving innovation in biotechnology and sustainable industries. It addresses social challenges by promoting equitable resource access and empowering rural communities through sustainable farming and forestry. By integrating sustainable practices across sectors, it provides solutions for energy, climate, and resource challenges, contributing to a resilient and equitable global future.
5. A sustainable bioeconomy requires several key conditions to ensure environmental, social, and economic benefits. Sustainable resource management is essential, including responsible use of biomass and protection of ecosystems. Agricultural and forestry land-use management needs to be improved in a sustainable way. Through a knowledge-based approach, more efficient and sustainable production methods must be applied to increase productivity while at the same time the negative environmental impacts are reduced, natural resources are regenerated, and biodiversity is preserved. Sustainable resource management includes closing of nutrient and material cycles and allocation of all bio-based resources in a way that maximal ecological, social, and economic benefits are achieved through a holistic approach and compliance with the "food-first principle." The use of bio-based resources should furthermore only be implemented when they perform more sustainable than the fossil alternative. Next, technological innovation is critical. Advanced biotechnologies and processes can, for example, improve resource use efficiency, maximize waste utilization, and reduce environmental impacts. Complementary to technological advances, new forms of organizing societal actors, business models and institutional innovations are key to foster transformation processes and

ensure a system change. The change to a sustainable economy requires sustainability-conscious producers and consumers who steer economic activities through their businesses, capabilities, targeted preferences, and choices. Consumer awareness and demand for sustainable products can drive the market toward environmentally friendly solutions or promote sufficiency approaches to reduce the resource consumption and to implement innovative and potentially more resource use efficient ways toward fulfilling demands fostering long-term sustainability in the bioeconomy. The societal transition in the bioeconomy is led by awareness raising, not only for the global challenges we face but also for ways to deal with them. Strong policy frameworks are also vital. Governments must implement regulations to prevent overexploitation of natural resources, incentivize sustainable practices, and support research and development. International cooperation can ensure fair resource distribution and global sustainability. Social equity is another cornerstone. The bioeconomy should prioritize fair access to resources, empower local communities, and ensure that economic benefits reach all stakeholders.

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Bioeconomy Concepts

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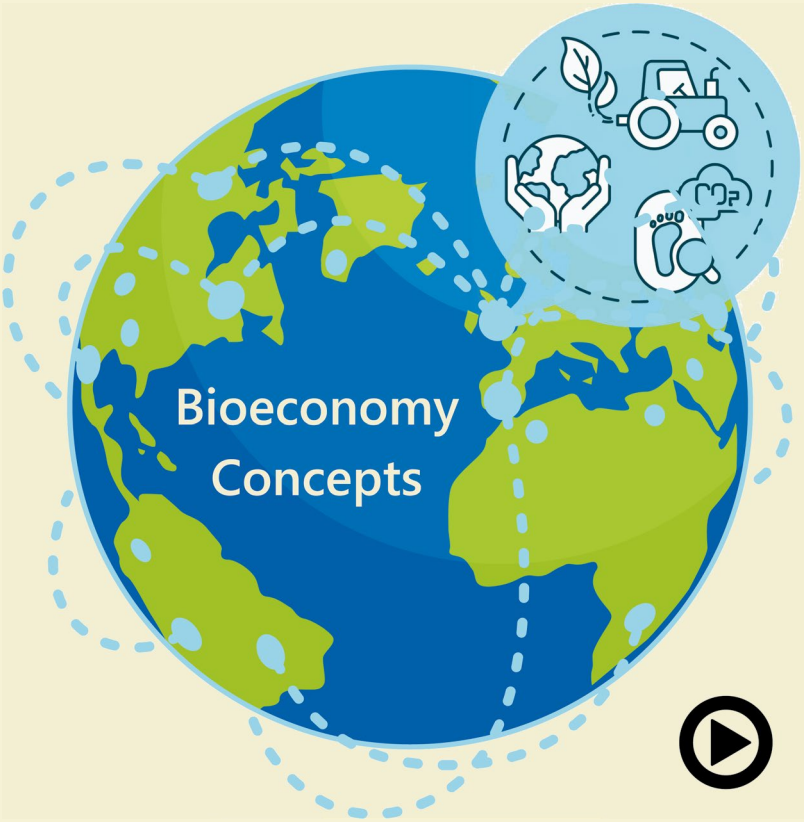


Fig. 2.0 Bioeconomy concepts (► https://doi.org/10.1007/000-htc)

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This chapter deals with the origin and evolution of the concept of the bioeconomy. It starts by tracing the first uses of the terms bioeconomics and bioeconomy and goes on to review the development of the concept of the 'knowledge-based bioeconomy' in the European Union before discussing the rise of the bioeconomy as a global concept. A shift from a 'resource substitution perspective' of the bioeconomy to a 'biotechnology innovation perspective' and lately to a 'green bioeconomy' is identified. Increasingly, bioeconomy strategies are evolving as enablers for sustainable development. Critical views of the bioeconomy are discussed, distinguishing a 'fundamental critique' and a 'greenwashing critique' of the bioeconomy. The last section also reviews the relations between the concept of the bioeconomy and the concepts of 'sustainable development', 'green economy', 'circular economy', 'socio-biodiversity' and 'transformation' and 'transition'.

Learning Objectives

After studying this section, you will…

- …be able to define the term bioeconomy (see ► Sect. 2.3).
- …be able to describe the origin and evolution of the concept of the bioeconomy (see ► Sects. 2.1 and 2.2).
- …be able to explain the diverse perspectives on the bioeconomy (see ► Sect. 2.3).
- …be able to identify regional differences in bioeconomy perspectives and strategies (see ► Sect. 2.2).
- …be able to explain the relation between the concept of the bioeconomy and the concepts of sustainable development, green economy, circular economy, socio-biodiversity and transformation and transition (see ► Sect. 2.3).

2.1 The Origin of the Concept of the Bioeconomy

2.1.1 The First Use of the Terms 'Bioeconomics' and 'Bioeconomy'

The use of the term 'bioeconomics' can, according to Bonaiuti (2014, p 54), be traced back to Zeman, who used the term in the late 1960s to designate an economic order that appropriately acknowledges the biological bases of almost all economic activities. As Bonaiuti (2014, p 54) further explained, Georgescu-Roegen 'liked the term and from the early 1970s made it the banner summing up the most important conclusions he had come to in a lifetime of research'. An essential element in Georgescu-Roegen's use of the term 'bioeconomics' was his concern that unlimited growth would not be compatible with the basic laws of nature (Bonaiuti 2014, p 54).

This use of the term 'bioeconomics' is rather different from the early use of the term 'bioeconomy', which referred to the use of biological knowledge for commercial and industrial purposes. One can consider this rather contrasting use of the two terms as an 'irony of fate'. Several authors (e.g. von Braun 2014, p 7, and Gottwald 2016, p 11) attributed the first use of the term bioeconomy to the writings of Juan Enriquez Cabot, a Mexican-American academic and businessman. In a paper entitled 'Genomics and the World's Economy', Enriquez discussed that the application of the discoveries of genomics will lead to a restructuring in the role of companies and industries 'in a way that will change the world's economy'. In this paper, he outlined 'the creation of a new economic sector, the life

sciences' (Enriquez 1998, p 925). Though this paper does not use the term 'bioeconomy' (as Eversberg et al. (2023, p. 569) point out, 'Enríquez never seems to have used the term "bioeconomy"—only "biotechonomy" is on record' (Enriquez 2002)'), the source represents one of the roots of the concept of bioeconomy: advancements in the biological sciences and in biotechnology, which have the potential to transform many industrial production processes. The view that the 'biological revolution' would eventually transform the industry was, however, not new at that time. The 'industrial impact of the biological revolution' was already formulated in the early 1980s (Glick 1982).

2.1.2 The Development of the Concept of the 'Knowledge-Based Bioeconomy' in the European Union

Even though the term 'bioeconomy' was first introduced by scientists concerned with the industrial consequences of advancements in biology, the major reason why bioeconomy became an important policy concept in Europe was a deliberate decision by staff members of the European Commission (EC) to promote this concept. One of the key actors in this effort was Christian Patermann, the former Program Director of 'Biotechnology, Agriculture and Nutrition' in the Directorate General for Research, Science and Education of the European Commission (EC). As specified by Patermann and Aguilar in a paper on 'The origins of the bioeconomy in the European Union' (Patermann and Aguilar 2018, p 22), the term 'bioeconomy' was used in two sources that inspired the Commission staff in the early 2000s. One was a document entitled 'Towards a bio-based economy—issues and challenges', which was published by the Canadian environment think tank Pollution Probe (2002). The other one was a document published by the OECD (2004), which defined a 'bio-based economy' as 'a concept that uses renewable bioresources, efficient bioprocesses and eco-industrial clusters to produce sustainable bioproducts, jobs and income' (OECD 2004, p 5). The document was based on a meeting of the 'OECD Committee for Scientific and Technological Policy at Ministerial Level' in January 2004. As Patermann and Aguilar (2018, p 22) explain, there is, unfortunately, 'no tangible information within the OECD archives of by whom the original idea of "bio-based economy", in particular the respective wording in the document, was coming from, or which Member State delegation had prompted or particularly supported it'. While the origins of the bioeconomy concept remain, thus, somewhat opaque, what is rather clear is that Patermann and his colleagues immediately realized the unique potential of the bioeconomy as an innovative policy concept that would allow the EU to respond to new opportunities. One opportunity was making economic use of the emerging new potential of using biotechnologies, as indicated above.

Another opportunity inherent in the concept of the bioeconomy is the replacement of fossil-based resources by bio-based resources, both for energy and for material use. In the early 2000s, decision-makers in the EU felt a strong incentive to find new concepts, because the need for increasing agricultural productivity to meet future needs for food and biomass was not very well recognized at the time. Funding for agricultural research, which is key to increasing agricultural productivity, had declined throughout the 1990s in spite of the emerging need to produce biomass for other uses than food (Geoghegan-Quinn 2013).

In developing the concept of the bioeconomy in the EU, the label 'knowledge-based' was added so that it became the 'Knowledge-Based Bioeconomy'. The label 'knowledge-based' was in line with the EU innovation policy that prevailed at the time. At a meeting in Lisbon in 2000, the European Council had made a commitment to establish 'the most competitive and dynamic, knowledge-based economy in the world' (EU 2000). The concept of the knowledge-based economy reflects the vision of achieving economic growth

through high-technology industries, which requires investments in innovation and highly-skilled labour.

The efforts of the EU to promote the concept the Knowledge-Based Bioeconomy proved remarkably successful. In 2005, the European Commission held a conference entitled 'New Perspectives on the Knowledge-Based Bio-Economy' (EC 2005). At this conference, Janez Potočnik, the European Commissioner for Science and Research at the time, gave a speech entitled 'Transforming life sciences knowledge into new, sustainable, eco-efficient and competitive products' (Potočnik 2005). In the so-called 'Cologne Paper' of 2007, this title has been quoted as a definition of the knowledge-based bioeconomy. The Cologne Paper was based on a workshop held under the German Presidency of the Council of the European Union in 2007 in the city Cologne. The workshop was attended by experts from research organizations and companies covering different fields, including crop production, biotechnology, bioenergy and biomedicine (EU 2007). The Cologne Paper emphasized the two dimensions of the bioeconomy mentioned above:

- On the one hand, the paper identified the role of biotechnology as 'an important pillar of Europe's economy by 2030, indispensable to sustainable economic growth, employment, energy supply and to maintaining the standard of living' (EU 2007, p 4). One can label this dimension of the bioeconomy 'the biotechnology innovation perspective'.
- On the other hand, the Cologne Paper stressed the use of crops as 'renewable industrial feedstock to produce biofuels, biopolymers and chemicals' (EU 2007, p 4). The paper also envisaged that 'by 2020, in addition to the then mature gasification technologies, the conversion of lignocellulosic biomass by enzymatic hydrolysis will be standard technology opening up access to large feedstock supplies for bioprocesses and the production of transport fuels'. One can label this dimension of the bioeconomy 'the resource substitution perspective'.

The changing emphasis of these two perspectives over time is further discussed in ▶ Sect. 2.3 below. The development of the concept of the bioeconomy was accompanied by increased funding, especially in the EU's Framework Programmes for Research and Technological Development. The 7th Framework Programme included a budget of almost two billion Euro for bioeconomy research and development, a remarkable achievement considering that the concept was still rather new when this program was designed (Patermann and Aguilar 2018, p 22). The subsequent EU Framework Programmes (Horizon 2020 and Horizon Europe) have continued to provide strong support for the bioeconomy (EC 2013, 2021).

The development of the bioeconomy concept by the institutions of the EU was mirrored by efforts to establish this concept in the EU member states. Germany, for example, established a Bioeconomy Council at the federal level in 2010 under the leadership of the Federal Ministry of Education and Science (BMBF). In 2010, the 'National Research Strategy BioEconomy 2030' was published (BMBF 2010), and the federal government pledged to spend 2.4 billion Euro for bioeconomy research until 2016 (BMBF 2014, p 9). In 2014, Germany published a 'National Policy Strategy on Bioeconomy'. The policy had the subtitle 'Renewable Resources and Biotechnological Processes as Basis for Food, Industry and Energy', which reflects both the biotechnology innovation perspective and the resource substitution perspective mentioned above. In 2020, this national bioeconomy policy strategy was updated by setting out the guidelines and goals of future bioeconomy policy and bundling research funding and the political framework for the bioeconomy (BMBF 2020). Two overarching guidelines accompany the goals and measures of the National Bioeconomy Strategy: (i) Biological knowledge and continued progressive technologies as pillars of a future-proof sustainable and climate-neutral economic system; and (ii) biogenic resources as the base for a sustainable and circular economy. The overarching strategic goal of this strategy is the alignment with the 17 sustainable develop-

ment goals (SDGs) of the UN (BMBF 2020), which are further discussed in ▶ Sect. 2.3.4 below.

Other European countries also developed policies and strategies related to the bioeconomy. There was considerable variation regarding the extent to which these policies and strategies were specifically focused on the bioeconomy or rather on related aspects, such as biotechnology or renewable energy. The publication of the European Bioeconomy Strategy in 2012, which is further described below, was followed by the development of national bioeconomy strategies in several European countries. Finland had already published a bioeconomy strategy in 2014. Austria and Norway, to mention two other examples, were in the process of preparing dedicated bioeconomy strategies in 2015 (BÖR 2015a). Between 2014 and 2020, another eight EU countries, including Austria, France, Ireland, Italy, Latvia, the Nordic Countries, and Spain, adopted dedicated bioeconomy strategies. As of 2024, there were eleven EU Member States that had dedicated bioeconomy strategies, while another seven were in the process of developing their strategies (IACGB 2024). Most of the national strategies have a specific focus. For example, Portugal emphasizes a 'blue' bioeconomy, which entails the knowledge-based production and utilization of aquatic bioresources for innovative products, processes, and services. In the meantime, many strategies have become very concrete in providing dedicated action plans, as in case of Austria, Ireland, Portugal, or in setting clear goals. An example is Finland, which aims to double the value added from its bioeconomy by 2035 in an ecologically, socially and economically sustainable way. Another development in the EU is the development of bioeconomy strategies at sub-national (regional) level. Many European regions or Federal States have integrated the bioeconomy into their policy agendas (IACGB 2024).

At the level of the European Union, the first European Bioeconomy Strategy and Action Plan was, as mentioned above, adopted in 2012 (EC 2012). Its main focus was promoting the transition from a fossil-based to a bio-based economy. In 2018, an updated version of the strategy (EC 2018a) was published together with an Action Plan (EC 2018b). The five headline targets of the initial 2012 version were (1) food security; (2) sustainable natural resource management; (3) increasing bioresources; (4) climate change mitigation and adaptation; and (5) job creation. These targets were retained in the 2018 version of the Strategy, but the scope was expanded by three new areas of action: (i) scaling-up of bio-based sectors and markets; (ii) deployment of bioeconomies across Europe; and (iii) operating within the ecological and planetary boundaries (Dolge et al. 2023; EC 2018a).

An updated version of the European Bioeconomy Strategy was released in November 2025 (European Commission (EC) 2025). It relates to the objectives of the Green Deal and emphasize the contribution of biotechnology and biomanufacturing. The Green Deal was launched by the EC in 2019 and aims to reach climate neutrality of the EU by 2050 (EC 2019) (see Excursus 2.1 Green Deal and Bioeconomy below). In 2024, the EC launched a communication entitled 'Building the Future with Nature: Boosting Biotechnology and Biomanufacturing in the EU' (EC 2024). Both the title and the focus of the communication are consistent with the biotechnology innovation perspective identified above. As further discussed below, the communication also strongly relates to the executive order (EO) on bioeconomy, which was launched by the US in 2022 (White House 2022).

The update of the European Bioeconomy Strategy offered the opportunity to include the perspectives of the Youth. Bioeconomy Youth Ambassadors have been selected by the EC to represent the voice of the youth within the bioeconomy. In their paper on the 'Vision for Future Bioeconomy Policies', the European Youth Ambassadors describe their perspective on the bioeconomy as 'a holistic approach to achieving a resilient, circular, bio-based economy through a just-transition that consciously aims to reduce economic throughput within our planet's regenerative

capacity' (EU Youth Ambassadors 2024, p. 3). To shape future-oriented bioeconomy policies, they demand (i) the involvement of youth in decision-making; (ii) cultivating an inclusive debate, for example, through interdisciplinary and inclusive approaches in bioeconomy education as well as bioeconomy education at all levels; (iii) rethinking economics: from infinite to post growth; (iv) a responsible use of bio-based resources; and (v) an assessment of the true burdens and benefits of the bioeconomy (EU Youth Ambassadors 2024).

2.2 The Rise of the Bioeconomy as a Global Concept

The EU is not the only region of the world where the concept of the bioeconomy has been promoted since the early 2000s. As shown in the following, the first decades of the twenty-first century saw the rise of the bioeconomic as a global concept. As of 2024, more than 60 countries had dedicated or related bioeconomy strategies (see Fig. 2.1 below). Globally, the bioeconomy is increasingly seen as an enabler for sustainable development (see ▶ Sect. 2.3 below).

2.2.1 USA

In 2012, the Obama administration released an official US strategy on the bioeconomy entitled 'National Bioeconomy Blueprint' (White House 2012). This strategy defined the bioeconomy as follows:

'A bioeconomy is one based on the use of research and innovation in the biological sciences to create economic activity and public benefit. The U.S. bioeconomy is all around us: new drugs and diagnostics for improved human health, higher-yielding food crops, emerging biofuels to reduce dependency on oil, and bio-based chemical intermediates, to name just a few' (White House 2012, p 7). This definition reflects the two perspectives of the bioeconomy discussed above, the biotechnology innovation perspective and the resource substitution perspective. It is also notable that the US strategy strongly features the pharmaceutical industry as part of the bioeconomy.

On September 12, 2022, President Biden signed an Executive Order (EO) entitled 'Advancing Biotechnology and Biomanufacturing Innovation for a Sustainable, Safe, and Secure American Bioeconomy (White House 2022)'. The EO aims at framing the promo-

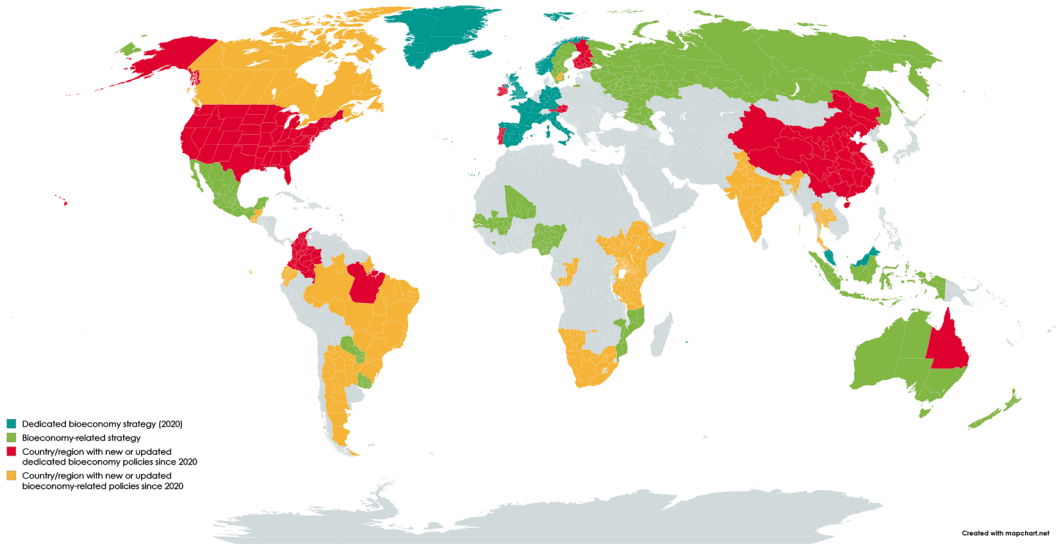


Fig. 2.1 Bioeconomy policies and strategies globally 2020–2024 based on IACGB (2024). (© Valentin Schlecht)

tion of bioeconomy development as a 'whole of government' task with commitments towards biotech research, development of the biotech workforce, enhanced support for biomanufacturing and the implementation of streamlined regulations aimed at lowering obstacles and reducing transaction costs (IACGB 2024). This strategy clearly puts an emphasis on the biotechnology innovation perspective.

2.2.2 Latin America and the Caribbean

In developing their bioeconomy strategies, the countries of Latin America and the Caribbean (LAC) focused on structural conditions that allowed them to use the bioeconomy as a development model. These include the mega-biodiversity of LAC countries (see ▶ Chap. 40), the important role of agricultural production as one of the main economic activities and a major contributor to their gross domestic product (GDP), the large amounts of residual biomass from agricultural production, and the high potential for expanding the production of bio-based resources (Rodríguez et al. 2019). In Brazil, early initiatives to foster the bioeconomy through bioenergy production were further promoted in 2004 with the National Biodiesel Program (PNPB) and in 2007 with the National Policy of Biotechnology Development (Aramendis et al. 2018). In Argentina, supporting actions towards national bioeconomy programs started in 2005 (Aramendis et al. 2018).

A collaboration with the emerging bioeconomy in the EU also contributed to the rise of the economy in the LAC region. An example is the bi-regional project 'Towards a Latin American and Caribbean Knowledge Based Bio-Economy in partnership with Europe' (2011–2013), which facilitated the identification of key areas for the bioeconomy in LAC countries (Trigo et al. 2013; Hodson de Jaramillo et al. 2019; Aramendis et al. 2018). Moreover, the regional organizations IICA (Inter-American Institute for Cooperation on Agriculture) and UN-ECLAC (UN Economic Commission for Latin American and the Carribean) promoted the bioeconomy as an engine for sustainable and inclusive growth and as a strategy for the transformation of the countries´ production systems. The promotion of the bioeconomy concept in the region strengthened the political willingness of LAC countries to design bioeconomy-related and sectorial policy strategies and programmes related to biotechnology, bioenergy and green growth (Siegel et al. 2022).

In the 2020s, dedicated bioeconomy strategies gained prominence in the LAC region. Until 2020, Costa Rica had been the only LAC country that had a dedicated national bioeconomy strategy (IACGB 2020). In 2019, Colombia started developing a national bioeconomy strategy that was officially released in 2020 with an emphasis on industrialization, territorial development and sustainable biodiversity use (Johnson et al. 2022; IACGG 2024; Ministerio de Ciencia, Tecnología e Innovación 2020). In 2024, Brazil launched a national holistic bioeconomy strategy (MDIC 2024; Glatzel et al. 2024). Among the objectives of this strategy, social aspects and biodiversity play a key role. In this context, a new perspective on the bioeconomy emerged, which has been labelled the 'socio-biodiversity bioeconomy' perspective (see ▶ Sect. 2.3.4 below and ▶ Chap. 40). This perspective is rooted in the aim to protect ecosystems and as well as social wellbeing and provide livelihood options to local communities in the forest areas of Brazil (IACGG 2024). This pathway is, for example, at the core of the state bioeconomy strategy of Pará, a state in the Brazilian Amazon region (Costa et al. 2020). Other LAC countries, such as Ecuador, Guatemala, Puerto Rico, Uruguay and Paraguay, have also started the process of developing dedicated bioeconomy strategies. Moreover, there are dedicated regional bioeconomy programmes and action plans for bio-based sectors and products, for research and development and for the use of biodiversity (IACGG 2024).

2.2.3 Asia

Shortly after the US EO, China released its 14th five-year plan, which also has a strong focus on the biotechnology innovation perspective. It contains the following key areas for development: (i) biomedicine for life and health; (ii) modernization of agriculture; (iii) green and low-carbon biomass applications; and (iv) national biosecurity risk prevention and control (IACGB 2024, p 22).

Other Asian countries, also published bioeconomy-related policies and strategies in the first two decades of the twenty-first century. For example, Malaysia already published a 'Bioeconomy Transformation Program' in 2012 (BÖR 2015a). Thailand and Japan also have dedicated bioeconomy strategies. Japan's national bioeconomic strategy is subject to annual revisions, and Thailand introduced a 'Bio-Circular-Green Economy' model as a strategic framework for national development and post-pandemic recovery (IACGB 2024, p 22).

2.2.4 Africa

The bioeconomy also evolved on the African continent. South Africa already published a dedicated bioeconomy strategy in 2013, which focused on innovations in health, agriculture, environment and indigenous knowledge (BÖR 2015a). Since then, the Eastern African countries Burundi, Ethiopia, Kenya, Rwanda, South Sudan, Tanzania and Uganda cooperated within the Network for Eastern African Development (BioInnovate Africa) to develop regional innovation-driven bioeconomy strategies. The East African Community (EAC) developed a bioeconomy strategy for its member states in 2022 (EAC 2022). EAC's mission is to promote integration, economic development, social progress and peace and security in the East African region. The EAC Strategy envisions the bioeconomy to drive sustainable economic growth in the region by creating jobs, making use of the region's bioresources for products and services and to contribute to environmental protection and climate change mitigation.

2.2.5 International Organizations

Another indication of the rise of the bioeconomy as a global concept is the inclusion of the bioeconomy into the strategies of international organizations. The Food and Agriculture Organization of the UN (FAO) included bioeconomy in its most recent science strategy (FAO 2024). FAO considers the bioeconomy as an opportunity for farmers and acknowledges the potential contribution of the bioeconomy to sustainable food and agriculture. The World Bank has also increasingly made use of the bioeconomy concept, for example, by supporting countries to develop their bioeconomy strategies (see, e.g. World Bank 2023).

2.2.6 Global Bioeconomy Summits

The rise of the bioeconomy as a global concept has also been promoted by the Global Bioeconomy Summits. In December 2015, the first Global Bioeconomy Summit (GBS) was held in Berlin. The event was organized by the German Bioeconomy Council in collaboration with the International Advisory Council on Global Bioeconomy (IACGB), an independent think tank with the mission to promote the global bioeconomy as a sustainable and future looking movement for the benefit of planet and people. GBS 2015 brought together more than 700 bioeconomy experts from more than 80 countries (BÖR 2015b, p 4). The German Bioeconomy Council and IACGB organized two more Global Bioeconomy Summits in Germany, which were held under the auspices and with support of Germany's Federal Ministries of Education and Research (BMBF) and of Food and Agriculture (BMEL). One was the GBS 2018, which was again held in Berlin and the other one was the GBS 2020, which was a virtual event due the Corona crisis at the time. Afterwards, the IACGB decided to hold the subsequent Global Bioeconomy Summits in different regions of the world. The GBS 2024 was held in Nairobi, Kenya. It was hosted by the East African Science and Technology

Commission (EASTECO) of the East African Community (EAC), the International Centre of Insect Physiology and Ecology (*icipe*), the program BioInnovate Africa, and the Stockholm Environment Institute (SEI) in collaboration with 14 other organizations that served as partners and sponsors. More than 500 participants came to Nairobi to attend the GBS 20204, and more than 3000 followed the summit online (See GBS24 2024).

The global view on the bioeconomy concept, as expressed in the GBS communiques, has evolved and widened over time, as can be seen in the comparison of the bioeconomy definitions provided in ▶ Sect. 2.3.4. Along with the communique of the IACGB in 2024, their Bioeconomy Youth Champions (BYC), representing 18 nationalities across the world, have published a 'Youth Communiqué: A Shared Vision for a sustainable global bioeconomic', in which they call to action for developing a sustainable bioeconomy and demand to: (i) empower Youth through education and inclusive policies; (ii) enhance infrastructure and resources for sustainable development; and (iii) foster national, regional, and global collaboration and innovation (IACGB Bioeconomy Youth Champions (BYC) 2024).

2.3 Evolving Perspectives on the Bioeconomy

The rise of the bioeconomy as a global concept has been associated with different perspectives, which have evolved over time. This section describes the evolution of these perspectives.

2.3.1 Overview of Different Perspectives

As shown above, the development of the concept of the bioeconomy was initially characterized by two perspectives: (1) the resource substitution perspective and (2) the biotechnology innovation perspective. The early papers that led to the evolution of the bioeconomy, such as the 'Cologne Paper' quoted above, already included references to climate protection as a justification for the bioeconomy (EU 2007, p 4). Moreover, the bioeconomy was generally regarded as a strategy to enable sustainable economic growth (see, e.g. EU 2007, p 4). However, as the bioeconomy concept was further developed during the second decade of the twenty-first century, it was increasingly recognized that environmental goals need to be included more explicitly into the bioeconomy concept as the use of biotechnological innovations and the use of bio-based resources are not 'automatically' more environmentally friendly than alternative options (Gawel et al. 2019). The increasing criticism of the use of bioenergy, which was associated with the food price crisis of 2008/2009, is a pronounced example of this shift in emphasis (see ▶ Sect. 2.3.3 below).

The literature on bioeconomy perspectives has been evolving in parallel with the development of the bioeconomy concept. Taking this literature into account (Bugge et al. 2016; Hausknost et al. 2017; Meyer 2017; Hoff et al. 2018; IACGB 2024), one can distinguish the following three clusters of major perspectives on the bioeconomy (See ◘ Table 2.1):

1. the resource substitution perspective;
2. the bio-technology innovation perspective; and
3. the green bioeconomy perspective, which encompasses the concepts of sustainability, circularity; socio-biodiversity as well as transition and transformation.

These perspectives correspond to the visions that Bugge et al. (2016) identifies in his literature review as the 'bio-resource vision', the 'bio-technology' vision and the 'bio-ecology' vision. 'Bio-ecology' refers to a branch of 'ecology dealing with the interrelation of plants and animals with their common environment' (Merriam-Webster 2024). Instead of this term, the label 'Green Bioeconomy' has been selected here as it encompasses a broader range of bioeconomy approaches than the term 'bio-ecology' suggests.

Table 2.1 Perspectives on the Bioeconomy

	(1) Resource Substitution Perspective	(2) Biotechnology Innovation Perspective	(3) Green Bioeconomy Perspective (sustainability; circularity; socio-biodiversity; transformation and transition)
Focus	Focuses on replacing fossil-based by bio-based resources (bioenergy, bio-based materials)	Focuses on research and application of life sciences and bio-technology in different sectors of the economy	Focuses on sustainability and the importance of ecological processes, including sustainable use of biodiversity and the relation with socio-cultural diversity
Main aspects	Resource management; emphasis on sustainable agriculture, forestry, and marine resources management; promoting practices that ensure long-term resource availability	Technological innovation and industrial transformation: investment in research and development (R&D) and collaboration with tech sectors to improve the efficiency of biological production processes	Sustainability, circularity, socio-biodiversity; transition and transformation; ecosystem services; sustainable use of and conservation of biodiversity in different ecosystem, including forests and agroforestry systems; regeneration of natural resources; diversification of value chains into value webs; social inclusion; traditional knowledge and practices
Major driving forces	Expectation that prices for fossil resources will continue to increase; climate change mitigation (e.g. Paris climate agreement)	Advances in the biological sciences; technological developments and commercial innovations	Climate change (e.g. Paris climate agreement); need to respect planetary boundaries and address biodiversity crisis and deforestation; recognition of role of local communities in sustainable use of agro- and forest ecosystems; goal of inclusiveness and equity
Overall rationale	Resource substitution and stimulating development in rural regions, regional resource autonomy	Achieve economic growth, improved international competitiveness, additional jobs	Place-based local and regional sustainable value chains; decentralized, territorial approaches; alternative forms of the economy; local development and small-scale production

Source: prepared by the authors

2.3.2 Early Perspectives: Resource Substitution and Biotechnology Innovation

Inherent in the concept of a bioeconomy is the challenge and the opportunity to replace fossil-based with bio-based resources (resource substitution perspective). A driving force behind this perspective was the concept of 'peak oil', which implies that oil extraction rates had reached its peak and that extraction rates would fall after the peak, while oil prices would continuously increase (Bardi 2009). A rising oil price increases the comparative advantage of using biomass. The oil price crisis of 2007/08 reaffirmed the 'peak oil' perception. The increasing use of food crops for biofuel contributed to the spike in food prices that was observed following the oil price crisis. This development was primarily triggered by high oil prices (Heady and Fan 2008). Biofuel policies, such as biofuel subsidies and mandates to add biofuel to commercial petrol, became subject to increasing criticism, as

researchers established the impact that they can have on food prices (deGorter et al. 2013). These developments had two important implications for the bioeconomy: First, the potential tension between ensuring food availability and using biomass for energy purposes became an important topic in the public policy debate surrounding the bioeconomy, as will be further discussed below. Second, increasing attention was paid to the need to increase the productivity of biomass production and to develop options for producing and using biomass that are not in conflict with food availability. Such options include second-generation technologies and the use of by-products and waste products for bioenergy production.

As both energy and food prices are more volatile as compared to the 1990s (Kalkuhl et al. 2016; Baumeister and Kilian 2016), the resource substitution perspective remains an important driver especially for countries with vast availability of biomass.

Figure 2.2 illustrates the resource substitution perspective of the bioeconomy. This diagram was developed by the German Bioeconomy Council in 2010 (BÖR 2010). Essential components of the bioeconomy are, as seen in Fig. 2.2, the production of biomass in various forms, its conditioning and conversion using different procedures, and the production and marketing of food, feed, fibre fuel, and 'fun'. The term 'fun' refers to products such as flowers.



Fig. 2.2 The Resource-substitution perspective of the bioeconomy

As shown above, the concept of the bioeconomy has, right from its very beginning, included a biotechnology innovation perspective next to a resource substitution perspective. This biotechnology innovation perspective refers to the application of innovative tools from the fields of biology and chemistry, which are key for the use of biotechnological processes and the generation of bioeconomy products in a wide range of economic sectors, including the chemical industry. Accordingly, the opportunity to make economic use of innovations in biotechnology and, more generally, in the life sciences has become a major rationale for this perspective on the bioeconomy.

A main target of this perspective is to enhance the competitiveness of the biotechnology sector in order to better utilize its potential. The bio-technological innovation perspective focuses on biotechnology's potential to make processes in a wide field of applications more efficient and sustainable. A prominent example is the use of enzymes in laundry detergents, which reduce greenhouse gas emissions by lowering the temperature required for household laundering (Al-Ghanayem and Babu 2020).

Other examples include the use of biotechnology for creating sustainable alternatives to fossil-based products, developing biofuels, enhancing crop yields, and producing eco-friendly chemicals. The aim is not only to foster the growth of bio-based industries but also to position a country's biotechnology sector as globally competitive and technologically advanced. This perspective considers biotechnology as integral to sustainable solutions in fields such as healthcare, agriculture, and industrial production, positioning it as essential for transitioning to a low-carbon economy while reducing ecological footprints across sectors. The section on 'Industrial Biotechnology' in the German Bioeconomy Policy Strategy of 2014 (BMEL 2014, p 31ff) illustrates this early perspective very well.

2.3.3 Criticism Against the Early Perspectives

The global rise of the concept of the bioeconomy has not been without its critics. This criticism contributed to 'the greening of the bioeconomy', which led to the set of perspectives presented in the third column of ◘ Table 2.1 One can distinguish two major types of criticism, which one can label the 'fundamental critique' and the 'greenwashing critique'.

2.3.3.1 The Fundamental Critique of the Bioeconomy Concept

The fundamental critique of the bioeconomy focuses not only on its environmental, but also on its social impacts. An example of the fundamental critique are the writings by Birch and co-authors (Birch 2006; Birch et al. 2010). They criticize the bioeconomy as the 'neoliberalization of nature'. The authors analyse the emerging discourse of the Knowledge-Based Bioeconomy in the EU and criticize that the development of the concept has been dominated by what they refer to as a 'neoliberal ideology'. Accordingly, the criticism of the bioeconomy concept is linked to a more general critique of 'a neoliberal regime in which market values are installed as the overriding ethic in society and the market rule is imposed on all aspects of life' (Birch 2006, p 4). Related to this type of criticism is the claim that the concept has been promoted to pursue the interest of big companies, which are interested in commercializing innovations in the life sciences and in applying technologies that are contested in society, such as genetic engineering and synthetic biology. This narrative also comprises the fear that a bioeconomy expansion can create uneven economic benefits. While it may boost rural economies by creating new markets for biomass, large agribusinesses often dominate, leaving smaller producers at a disadvantage and reinforcing economic inequality in certain areas

of the developing world (Bastos Lima 2021; Backhouse 2021; Backhouse et al. 2022).

The fundamental critique of the bioeconomy often focusses on the resource substitution perspective. An example is a paper by Gottwald and Budde that was published in 2015 on the occasion of the Global Bioeconomy Summit of 2015. These authors argue that the bioeconomy would promote 'land grabbing' and threaten world food security (Gottwald and Budde 2015). In essence, this type of critique makes the argument that an increased use of biomass demand in the EU will exacerbate global land use competition and pressures on ecosystems (Fleischmann et al. 2024). The critics also point out that as a result of this growing demand for biomass, prices for raw commodities—like crops used for food—might increase, which will threaten food affordability and security. Critics also point out that this can disproportionately impact rural and indigenous communities, raising ethical concerns about the fair distribution of benefits and land rights (Sarmiento Barletti et al. 2021; Dauvergne and Neville 2010). This criticism has led to a narrative shift toward a more inclusive bioeconomy, one that calls for equitable participation of small and local producers. Moreover, this criticism called for a 'food first' objective, which had—however - already been formulated in the Communiqué of the first Bioeconomy Summit of 2015 (IACGB 2015).

Another version of the fundamental critique focuses on the bioeconomy's reliance on biotechnological and synthetic innovations, which is seen as a form of 'technological fix' that does not address the underlying problems of overconsumption and waste (see, e.g., Lühman and Vogelpohl 2023). Critics also argue that the increasing use of biomass for energy and materials can put added pressure on ecosystems (Muscat et al. 2021; O'Brien et al. 2015). This growth risks surpassing biophysical limits, meaning the quantity of biomass that can be sustainably harvested without exceeding the land and ecosystems' regenerative capacity (Erb and Gingrich 2022).

These types of fundamental critique of the bioeconomy can be linked to a clash between two paradigms or worldviews regarding environmental policy. They have been described by Mann (2018) as the 'wizard's' and 'prophet's' paradigm. The 'wizard's paradigm' is associated with a focus on technological innovations as solution to environmental problems, whereas the 'prophet's paradigm' holds that environmental problems can only be resolved by cutting back consumption in order to respect environmental limits.

Mann (2018) traces these perspectives back to influential personalities. The wizard is associated with Norman Borlaug, whose path-breaking innovations in crop breeding made an unprecedented increase in crop productivity possible. The prophet is associated with William Vogt, a pioneer of the environmental movement. In his book 'Road to Survival', published in 1948, Vogt warned against the effects of population growth, increased consumption and the associated environmental effects (Vogt 1948).

The proponents of the bioeconomy are often associated with the wizard's perspective, as they focus on technological innovations, whereas the fundamental critics often represent the 'prophet's' perspective, as they warn against the possible negative effects of bioeconomy innovations and emphasize the limits of growth. As Barben et al. (2021) point out, these two perspectives are not necessarily exclusive, since bioeconomy policies could at the same time pursue sustainable innovations as well as a reduction in consumption.

2.3.3.2 The 'Greenwashing Critique' of the Bioeconomy Concept

The second type of critique of the bioeconomic can be interpreted as an effort to bring the wizard's and the prophet's perspective together. Hence, this criticism is not fundamentally opposed to the concept of the bioeconomy, but rather makes it clear that the bioeconomy is not 'automatically' sustainable. Consequently, this critique warns against the use of the bioeconomy concept for 'greenwashing'. An early example of this type of critique is a report by the World Wide Fund

for Nature published in 2009 (WWF 2009), which is entitled 'Industrial biotechnology—More than green fuel in a dirty economy?' This report acknowledges the potential of the bioeconomy to make modern economic systems more environmentally sustainable, but points out that the approaches that have been promoted under the label bioeconomy do not necessarily realize this potential. The thrust of this criticism is to ensure that the label 'bio' is not misused to portray an essentially non-sustainable economic system as environmentally friendly, but to ensure that innovations in the life sciences are indeed used to ensure a transition towards a sustainable economic system.

Critics who argue that the bioeconomy is not necessarily sustainable also point to the problem of the so-called 'rebound effects', which is an important concept in environmental economics. A rebound effect occurs, when improvements in resource efficiency, e.g. in the production or conversion of biomass, lead to increased overall consumption. The underlying mechanism causing this effect is improved efficiency, which reduces the price of the respective good and, hence, increases the demand for it. This kind of criticism has been formulated by authors who emphasized the need to make the bioeconomy circular, as a rebound effect may occur, for example, when re-circulated products cannot effectively compete with primary production products, leading consumers to buy more disposable items, thereby increasing the overall environmental impact (Salvador et al. 2021, p 11; Zink and Geyer 2017) (see also ▶ Sect. 3.3).

The scepticism and criticism associated with the bioeconomy concept has been important in stimulating a productive debate and an exchange of information, ideas and values. This has had beneficial effects on the development of the bioeconomy paradigm, as will be further discussed in the next section.

Do you want to learn more about the criticism against the bioeconomy? Take a look at Supplementary Video 2.1, a video from our MOOC 'Concepts of Sustainable Bioeconomy' (2021).

2.3.4 'Greening' the Bioeconomy

The rising criticism that the bioeconomy is not per se sustainable contributed to a process that has been described above as 'greening the bioeconomy'. This evolution reflects a broader, more mature understanding of bioeconomy, one that sees sustainability as a core principle rather than an optional add-on, thus making the bioeconomy an essential player in the transition to a circular, climate-resilient economy. The process of 'greening the bioeconomy', comprises a set of different 'green perspectives', including the alignment of bioeconomy with the concepts of sustainability, making the bioeconomy part of a green and a circular economy, linking the bioeconomy to socio-biodiversity, and using the bioeconomy as a strategy of economic and societal transition and transformation. These perspectives are described in more detail in the following.

2.3.4.1 Bioeconomy and Sustainability

The increasing concern about ensuring sustainability is reflected in an adjustment of the definition of the bioeconomy over time. The Communiqué of the Global Bioeconomy Summit of 2015, which was entitled 'Making Bioeconomy Work for Sustainable Development', included the following definition:

> Bioeconomy is defined in different ways around the world. We have not aimed for a unified definition but note that an understanding of "bioeconomy as the knowledge-based production and utilization of biological resources, innovative biological processes and principles to *sustainably* provide goods and services across all economic sectors" is shared by many (IACGB 2015, p 4, emphasis added).

At the 2018 GBS, this definition was extended in the Communiqué titled 'Innovation in the Global Bioeconomy for Sustainable and Inclusive Transformation and Wellbeing' as follows:

> Bioeconomy is the production, utilization and conservation of biological resources,

including related knowledge, science, technology and innovation, to provide information, products, processes and services in all economic sectors aiming *toward a sustainable economy* (GBS2018 Communiqué 2018, p.4, emphasis added).

This global view on the bioeconomy concept has further evolved and became wider over time as can be seen in the most recent definition of the bioeconomy provided in the 2024 GBS Communiqué, which includes sustainability aspects related to social and biodiversity features and explicitly includes the notion of economic transformation:

» The bioeconomy is the production, utilization, conservation, and regeneration of biological resources, including related knowledge, science, technology and innovation, to *provide sustainable solutions* (information, products, processes and services) within and across all economic sectors and *enable a transformation to a sustainable economy*. The bioeconomy is not a static notion and its meaning is *continually evolving* (GBS 2024 Communiqué, p.1, emphasis added).

The reference to sustainability can be placed within the context of the wider societal goal of 'sustainable development'. This concept had entered the international policy agenda already in the 1980s. The UN Commission on Environment and Development defined 'sustainable development' in its report 'Our Common Future' as follows:

'Development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (WCED 1987, p 41). The Commission on Environment and Development is also known as the Brundtland Commission, named after its chair, Gro Harlem Brundtland, who was then prime minister of Norway and first political leader who came to this position after having been a minister of environment before. As Brundtlandt points out, the Commission aimed at bringing two major concerns together, which had been emerged in the international agenda in previous decades but were hitherto treated rather independently: the concern about environmental problems in industrialized countries on the one hand, and the concern about poverty and population pressure in developing countries on the other hand (WCED 1987). The definition of sustainable development reflects the goal to address these two concerns jointly. The concept of sustainable development was reaffirmed at the 'International Conference on Environment and Development' in Rio de Janeiro in 1992, also referred to as the Rio Earth Summit. At this Conference, the representatives of more than 170 nations passed a major global action program called 'Agenda 21', which had four program areas: social and economic dimensions, conservation and management of resources, strengthening major groups, including civil society organizations, and means of implementation (UN 1992). The Agenda 21 promoted the notion that 'sustainable development' has three dimensions: an economic, a social and an environmental dimension. Accordingly, the principle that the bioeconomy has to be sustainable covers not only the environmental dimension, but also the economic and social dimension. The concept of sustainability and its relevance for the bioeconomy is further discussed in ▶ Chap. 3 of this book. At the Rio+20 Conference in Rio de Janeiro in 2002, the participants adopted a resolution entitled 'The future we want' (UN 2012). The international community hereby also agreed on a process to establish sustainable development goals as a follow-up to the Millennium Development Goals that had been agreed upon in 2000 and covered the time period until 2015 (UN 2012, p 46ff). A set of 17 'Sustainable Development Goals' (SDGs) were adopted by the UN in 2015. Learn more about the SDG on ▶ this website.

As the review by Bugge et al. (2016) showed, the alignment of the bioeconomy with sustainability goals led to new aspects for bioeconomy development, such as the cascading use of biomass; the optimization of energy and nutrient use; the conservation of biodiversity; and the promotion of soil health and agro-ecological practices. The need to make the bioeconomy sustainable also called for moving from bio-based value chains to value webs, which are created by the cascading use of bio-based materials (Scheiterle et al. 2018).

To ensure a sustainable bioeconomy, life cycle assessments have also gained importance (see e.g. Sinkko et al. 2023 and ► Chap. 41).

Since the SDGs include social goals, aligning the bioeconomy with sustainability principles also led to an emphasis on environmental justice, stakeholder participation and respect for ecological limits to ensure that growth in bio-based sectors does not lead to social inequities (see, e.g. van der Veen et al. 2024).

The bioeconomy has also grown to play a central role especially in major sustainability efforts, for example, in policy frameworks such as the EU Green Deal.

Excursus 2.1: The EU Green Deal and Bioecon omy

The European Green Deal is an ambitious initiative aimed at transforming the EU into a climate-neutral, resource-efficient economy by 2050. It was formulated as a Communication of the European Commission' in 2019 (EC 2019b) and approved by the European Parliament in early 2020. It formed the basis of a set of policy initiatives in different sectors, including the 'Farm to Fork' Strategy for the agricultural and food sector (EC 2019a). The bioeconomy plays a critical role in supporting this vision by advancing the shift from fossil-based to renewable, bio-based resources. This transition is essential within the Green Deal framework, as it aligns with its goals of reducing carbon emissions, preserving ecosystems, and promoting sustainable development. Through the financial support, policy guidance, and regulatory incentives embedded in the Green Deal, bioeconomy development is prioritized as a vital pathway to achieving a sustainable, climate-neutral Europe. The EU Green Deal positions the bioeconomy as a way to meet climate goals by reducing reliance on fossil resources and enhancing carbon sequestration, especially through practices in agriculture, forestry, and energy.

The sustainability perspective has also promoted a shift in focus from the supply-side of the bioeconomy to the demand-side, that is, a shift from technological innovations and companies that commercialize them to the consumers and to society at large. This trend can be seen, for example, in the recent European Commission (EC) Bioeconomy Progress Report, which emphasizes that 'consumption patterns need to become more sustainable to guarantee environmental integrity, as technological solutions alone cannot close the gap between sustainable supply of biological resources and demand' (EC 2022).

2.3.4.2 Bioeconomy and the Green Economy

In the UN Resolution 'The world we want' (UN 2012) mentioned above, the concept of the 'green economy' as 'one of the important tools available for achieving sustainable development' (UN 2012, p 10) was highlighted. The United Nations Environment Program (UNEP) defined a green economy.

» as one that results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities […] In its simplest expression, a green economy can be thought of as one which is low carbon, resource efficient and socially inclusive (UNEP 2011, p 16).

Excursus 2.2: Low Carbon Economy

A low-carbon economy focuses specifically on reducing carbon emissions to address climate change. This approach prioritizes energy efficiency, renewable energy (like wind, solar and bioenergy), and innovations that cut carbon output in sectors like transportation, industry and power generation. The main goal is to lower greenhouse gas emissions while maintaining economic growth (Sengupta et al. 2019).

In the academic literature, the concept of the green economy has a long history (see review by Loiseau et al. 2016).

> A ***green economy*** aims to preserve biodiversity, reduce pollution, manage waste responsibly and ensure the sustainable use of natural resources. It encompasses social equity, advocating for economic growth that benefits all parts of society and minimizes environmental degradation overall (Bailey and Caprotti 2014).

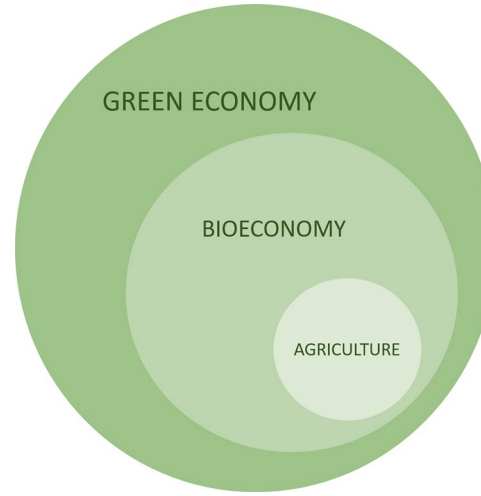


Fig. 2.3 The bioeconomy as a component of the green economy

The question arises as to how the concept of bioeconomy is linked to the concept of the green economy. Ultimately, this is a matter of definition. One option is to consider the bioeconomy as an integral component of the green economy. According to this view, one may consider renewable energy sources that do not rely on biological resources, such as wind and solar energy, as part of the green economy but not as part of the bioeconomy. Figure 2.3 below illustrates this conceptualization.

2.3.4.3 Bioeconomy and the Circular Economy

Next to the concept of the green economy, another concept has gained prominence in recent years: the concept of a 'circular economy'. The Communiqué of the 2015 Global Bioeconomy Summit mentioned above emphasized the need to align the principles of a sustainable bioeconomy with the principles of a circular economy, which 'would involve systemic approaches across sectors (i.e. nexus thinking), particularly innovation policy measures that aim at optimizing Bioeconomy value networks and minimizing waste and losses' (Bioeconomy Summit 2015, p 5). By 2024, the concept of circularity had become even more prominent. The GBS2024 Communiqué frequently refers to the concept of circularity, as in the following statement: 'During the last 10–15 years, the bioeconomy has indeed developed from a research driven field of experts to a cross-sectoral and inclusive model for a *circular* and sustainable economy' (GBS 2024, p 5, emphasis added).

This concept of the circular economy was popularized in a classical textbook on environmental economics by David Pearce and Kerry Turner in 1989 (Pearce and Turner 1989). These authors trace it back to a landmark essay by Kenneth Boulding published in 1966, in which Boulding emphasized the need to manage the economy not as an open system but as a 'spaceship', where 'man must find his place in a cyclical ecological system which is capable of continuous reproduction of material form' (Boulding 1966, p 112.) As a review by Ghisellini et al. (2016) shows, the concept of the circular economy has mostly been associated with the adoption of closing-the-loop production patterns within an economic system, and with aims to increase the efficiency of resource use, placing a specific focus on urban and industrial waste (Ghisellini et al. 2016, p 11). As such, the concept of the circular economy is narrower in scope than the concepts of the green economy and the bioeconomy. The demand to link the bioeconomy with the principles of the circular economy can, however, play an important role in ensuring that the bioeconomy is, indeed, sustainable (see ▶ Chap. 3). Moreover, the focus on renewable resources and on biotechnological innovations, which are central elements of the bioeconomy,

can play an important role in implementing the principles of the circular economy.

An increased emphasis on linking the concept of the bioeconomy with the concept of circularity can be seen in the rising use of the term 'circular bioeconomy'. This term has, for example, been used by the European Commission to underscore the importance of circular principles in bio-based processes. In the EU, this inclusion of circularity principles in the bioeconomy was also marked by the transition from the Bio-Based Industries Joint Undertaking (BBI JU) to the Circular Bio-based Europe Joint Undertaking (CBE JU).

Excursus 2.3: Bio-Based Industries Joint Undertaking (BBI JU)

The Bio-Based Industries Joint Undertaking (BBI JU) was a public-private partnership between the European Union and the Bio-based Industries Consortium (BIC), initiated through the EU Bioeconomy Strategy in 2012. Launched in 2014, BBI JU was part of the EU's Horizon 2020 research and innovation program. Its purpose was to accelerate the development of sustainable and innovative bio-based products and materials by funding projects.

The Circular Bio-based Europe Joint Undertaking (CBE JU) is the successor to BBI JU, launched as part of the EU's Horizon Europe program (2021–2027). CBE JU aims to build on BBI JU's foundation but with an expanded vision that includes the principles of a circular economy. This stronger focus towards embedding circular economy principles into Europe's bio-based industry is aligned with the EU's sustainability and climate goals (e.g. the EU Green Deal) and emphasizes the need to close resource loops and minimize waste throughout the economy.

Excursus 2.4: Circular Bio-based Europe Joint Undertaking (CBE JU)

The Circular Bio-based Europe Joint Undertaking (CBE JU) represents a €2 billion public-private partnership between the European Union and the Bio-based Industries Consortium (BIC), aimed at advancing competitive, circular bio-based industries within Europe. CBE JU's mission is to synergize efforts across a broad spectrum of stakeholders—from agricultural producers to research scientists—to address the sector's technological, regulatory, and market challenges. Through its collaborative funding model, CBE JU enhances innovation capacity, accelerates market integration of bio-based solutions, and facilitates pathways for future investment and development in the European bioeconomy.

The concept of circularity and its relevance for the bioeconomy is further discussed in ► Chap. 3 of this book.

2.3.4.4 Bioeconomy and Socio-Biodiversity

In recent years, the biodiversity crisis has become, next to the climate crisis, a driving force of bioeconomy development. Global concerns about the loss of biodiversity have a long history and they stimulated the development of the Convention on Global Biodiversity, which signed by 150 government leaders at the Rio Earth Summit mentioned above. The Framework Convention on Climate Change had been signed at the same occasion, but while climate change was an early driver of the bioeconomy, biodiversity conservation has become more prominent only in recent years (IACGB 2024; Bastos Lima and Palme 2022).

As pointed out above, it was in particular the development of the bioeconomy in the Latin American region, which identified the unique potential of the bioeconomy to con-

tribute to biodiversity conservation. This bottom-up perspective is rooted in forest regions of Latin America. Importantly, this perspective integrates the relations between two main elements: biological diversity and sociocultural diversity. The term 'socio-biodiversity' has been coined to capture this link, which was then associated with bioeconomy, resulting in the concept of 'socio-biodiversity bioeconomy' (Costa et al. 2020; Ribeiro et al. 2020; Saes et al. 2023). This perspective is also relevant for other regions of the world, which have important forest territories where the use of local biodiversity resources (e.g. non-timber forest products) is interlinked with cultural identity and local livelihood options. As has been pointed out above, different bioeconomy policy strategies of LAC emphasize the conservation of biodiversity by its sustainable use and potential for developing inclusive local value chains, as in the national bioeconomy strategies of Colombia, Brazil and Costa Rica. This perspective places emphasis on regionalized solutions, the participation of local communities, the development of fair and inclusive livelihood options, the promotion of agroforestry and the diversification of agriculture based on biodiversity, e.g., by promoting minor, novel and indigenous crops (Ollinaho and Kröger 2023). This perspective also highlights the role of traditional knowledge and cultural identity in forest areas, to the point of considering other forms of economic relations and value systems, which go beyond utilitarian relations with nature. Thus, this perspective differs from other bioeconomy perspectives and addresses the fundamental critique of the bioeconomy described in ▶ Sect. 2.3.3 above (Bastos Lima and Palme 2022; de Queiroz-Stein and Siegel 2023; de Queroz-Stein et al. 2023; Ollinaho and Kröger 2023). The linkages between bioeconomy and biodiversity are further discussed in ▶ Chap. 40 of this book.

2.3.4.5 Bioeconomy as a Transition and Transformation Strategy

As can be seen from the above definitions, the development of the bioeconomy concept was initially characterized by a focus on the 'supply-side' of the bioeconomy, that is by a focus on the supply of goods and services that are based on biological resources and biotechnological processes. In recent years, more emphasis has been placed on the demand-side of the bioeconomy and, more generally, on the role of the bioeconomy in society (see ▶ Chap. 36).

Figure 2.4 represents a more holistic view of the bioeconomy, which takes people—as consumers and citizens—explicitly into

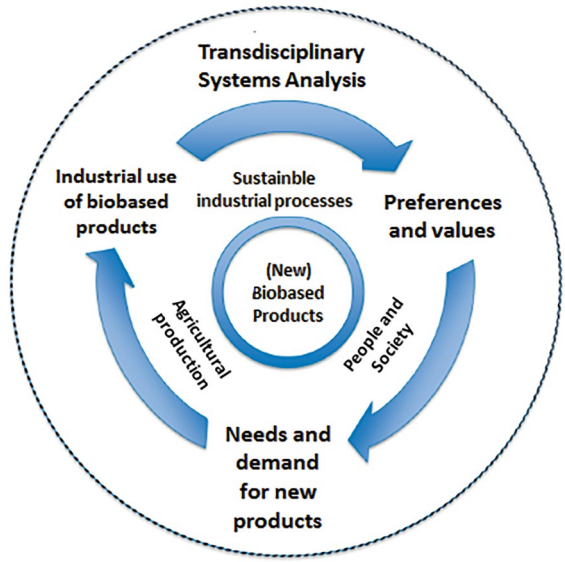


Fig. 2.4 Holistic concept of the bioeconomy

account. This diagram was developed by a team from the University of Hohenheim as basis for the Master Program 'Bioeconomy', which started in 2014.

As shown in the diagram, preferences and values of people, which translate into needs and demands for (new) bio-based products, are as essential for the bioeconomy as is the production of those products. This holistic view of the bioeconomy requires a transdisciplinary systems analysis. The issue of transdisciplinarity is dealt with in ▶ Chaps. 3 and 37 of this book. Taking the societal embeddedness of the bioeconomy a step further, one can also consider the bioeconomy as an essential element in a process of an economic and societal transformation or transition, which is required to transform the current economic system into one that is economically, environmentally and socially sustainable.

Excursus 2.5: Bioeconomy Transition Versus Bioeconomy Transformation

The development of the sustainable bioeconomy requires a far-reaching change of the current economy and society. While often used interchangeably within the context of the bioeconomy (e.g. Urmetzer et al. 2020), transition and transformation are two concepts that describe different types of change (Hölscher et al. 2018):

- Transition refers to a gradual process of moving from one state or condition to another, usually within a familiar framework or system. It involves incremental adjustments rather than a complete overhaul. Transition processes refer to how change is happening, in particular by envisioning a step-by-step approach.
- Transformation implies a profound and fundamental change, resulting in a new form, structure, or identity. It is often systemic and irreversible, requiring deep changes across multiple levels. The term transformation is also often used in normative statements, referring to what should be changed.

The bioeconomy embodies aspects of both transition and transformation: Developing a bioeconomy ultimately demands a transformative approach to different sectors, including energy, agriculture and industry. It also requires a transformative approach to consumption. This is because the bioeconomy redefines the fundamental resources that power modern economies, shifting the basis from finite to renewable, bio-based resources. This process is not merely about substituting materials. According to the biotechnology innovation perspective, it also requires integrated innovative technologies, such as biorefineries and synthetic biology. The bioeconomy also demands changes in policies, societal values and consumption patterns, as it requires a rethinking of the relationship between human activity and nature. As Barben et al. (2021) point out, the bioeconomy is not likely to evolve by itself, it requires the political will to implement game-changing measures and create conducive conditions for its development, especially since existing policy frame conditions often support industries that rely on fossil-based resources. However, especially the early stage of the bioeconomy development includes transitional elements, such as the implementation of biofuels as bridge technology for the defossilization of the economy, or the use of digital tools for the implementation of sustainable intensification of agricultural practices. Moreover, a bioeconomy transformation requires transitional step-by-step changes, because disruptive changes are difficult to pursue in democratic systems, as it is challenging to build the political support that they require.

In essence, bioeconomy transition and transformation are two relevant aspects of a change process that are largely interrelated and often merge into each other. Therefore, the interchangeable use of the two terms is understandable.

2.4 Conclusion

2

As this chapter has shown, the bioeconomy entails a multifaceted set of concepts and perspectives, which have been continuously evolving over time, partly in response to criticism. In spite of its diversity and evolving nature, the bioeconomy has emerged as a globally relevant concept, which has demonstrated a unique capacity to integrate different perspectives. This is impressively demonstrated by the Global Bioeconomy Summits, which have provided a forum where a global community has developed a shared vision of the bioeconomy, which acknowledges diversity and supports locally different goals and strengths (IACGB 2024).

Questions

1. How is the bioeconomy defined and how did this concept evolve over time?
2. What characterizes the resource substitution perspective of the bioeconomy on the one hand and the biotechnology innovation perspective on the other hand?
3. Which types of criticism have been formulated against the concept of the bioeconomy?
4. What are the relations between the concept of the bioeconomy and the concepts of sustainable development, green economy, circular economy, socio-biodiversity, and transition and transformation?

Answers

1. The bioeconomy has been defined by the Global Bioeconomy Summit of 2024 as 'the production, utilization, conservation, and regeneration of biological resources, including related knowledge, science, technology and innovation, to provide sustainable solutions (information, products, processes and services) within and across all economic sectors and enable a transformation to a sustainable economy'. The concept of a knowledge-based bioeconomy was first promoted in the European Union starting in the early 2000s. Since then, it emerged as a global concept, as an increasing number of countries in all regions of the world adopted dedicated or bioeconomy related policies and strategies.
2. The resource substitution perspective of the bioeconomy focuses on the replacement of fossil-based resources by bio-based resources, especially in the form of bioenergy and bio-based materials. This perspective was initially driven by concerns about limited resource availability ('peak oil') and later by the goal to reduce greenhouse gas emissions. The biotechnology innovation perspective focuses on the application of biotechnological innovations in industrial and agricultural production processes. This perspective has been driven by the goal to harness advances in the biological and life sciences.
3. One can distinguish two types of critique against the concept of the bioeconomy: a fundamental critique and a 'greenwashing' critique. The fundamental critique considers the bioeconomy as a 'neo-liberalization of nature' and argues that nature should not be made subject to the market mechanism. Concerns about a competition between food security and the use of biomass for bioenergy and bio-based materials have also led to a fundamental critique of the bioeconomy. The 'greenwashing' critique acknowledges the potential of the bioeconomy to contribute to a sustainable economy, but emphasizes that bioeconomy solutions are not necessarily sustainable, for example, due to rebound effects. Hence, it is, according to this critique, important to ensure that the bioeconomy is not misused for 'greenwashing' an unsustainable system.
4. The bioeconomy has increasingly been recognized as a strategy to contribute to sustainable development and to reach the sustainable development goals (SDGs). It can be seen as a component of a green economy, which has been defined as a low carbon, resource efficient and socially inclusive economy.

Bioeconomy can be part of a circular economy, especially if a cascading use of biomass is promoted and if bio-based value webs are developed for this purpose. The socio-biodiversity perspective of the bioeconomy focuses on the conservation and sustainable use of biodiversity, e.g. by promoting minor, novel and indigenous crops and by fostering the participation of local communities, while respecting their traditional knowledge and socio-cultural traditions. The concept of transition refers to an incremental change towards a more sustainable economy and society, whereas the concept of a transformation focuses on a profound and fundamental change. The bioeconomy can contribute to both types of processes.

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Guiding Principles of a Bioeconomy

Valentin Schlecht, Marielle Trenkner, Andrea Knierim, and Ricardo Vargas-Carpintero

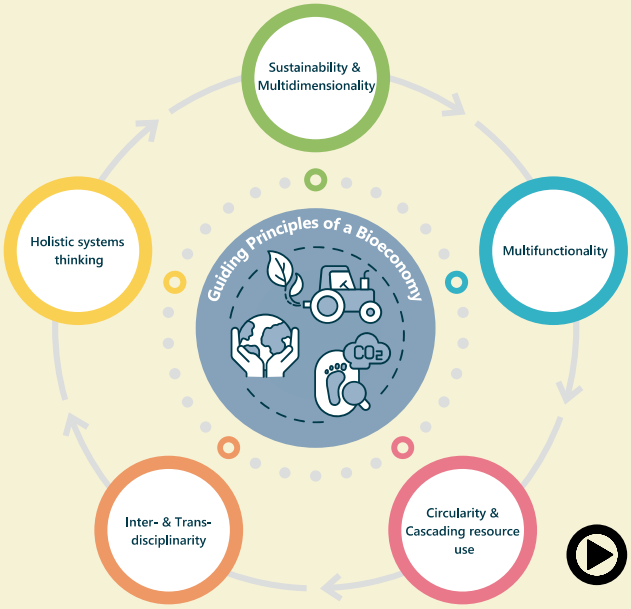


Fig. 3.0 Guiding principles of a bioeconomy (▶ https://doi.org/10.1007/000-htd)

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3

The bioeconomy, which encompasses the production, conversion and use of renewable biological resources, offers a pathway for the transformation of our society by promoting sustainable, knowledge-based innovation. The ultimate goal of the bioeconomy is to ensure the wellbeing of present and future generations within planetary boundaries, while also ensuring the continuous regeneration of ecological functions and ecosystem services.

In this chapter, we propose principles that place the bioeconomy concept in a broader context. Key principles guiding the bioeconomy transformation include:

- Sustainability: Ensuring the long-term health of the environment and regeneration of resources.
- Multifunctionality: Foster the capacity to fulfil multiple purposes simultaneously
- Circularity and cascading use of biomass: Promoting resource sequential use and recycling to create closed-loop systems.
- Inter- and Transdisciplinarity: Combining knowledge from various fields and engaging diverse stakeholders.
- Holistic systems thinking: Considering the entire life cycle of biological resources, contextual conditions, and stakeholder perspectives.

These principles act as 'universal' basic truths, general conditions or descriptive elements to achieve a bioeconomy and form a 'guard rail' for the transformation.

Learning Objectives

After studying this chapter, you will…

- …be able to describe the principles and goals of the Bioeconomy (see ► Sects. 3.1, 3.2, 3.3, 3.4, and 3.5).
- …be able to explain how the bioeconomy integrates knowledge from various fields and involves multiple stakeholders to achieve its sustainability goals, fostering collaboration across disciplines (see ► Sects. 3.4 and 3.5).
- …be able to apply the principles of circularity and cascading use of biomass to identify strategies to promote the reuse, recycling, and cascading use of biomass within closed-loop systems, and to illustrate how these practices contribute to a more sustainable bioeconomic transformation (see ► Sect. 3.3).
- …be able to delineate the role of holistic systems thinking in the bioeconomy to ensure sustainability and ecosystem regeneration in bioeconomic practices (see ► Sect. 3.5).

It may come as no surprise that the world is increasingly facing complex challenges. Today we are confronted with situations where things that were considered separate decades ago are now colliding with each other. Decisions made in the past on natural resource management have created long-term effects that lead to perturbations in planetary functions today. As our existing socioeconomic systems are transgressing several planetary boundaries (Rockström et al. 2009; Steffen et al. 2015; IPCC 2018; Richardson et al. 2023) we are experiencing radical technological and socio-ecological changes that are leading to a rethinking of our economic and societal models (e.g. global energy supply). This complex situation where multiple global crises (e.g. climate change, biodiversity loss) and societal challenges (e.g. poverty, hunger and inequality) are interconnected requires bridging the gap between current systems and new visions.

Our society requires a holistic transformation that can facilitate a positive change. The bioeconomy—the production, conversion and use of renewable biological resources and knowledge for the provision of bio-based products and services along with the generation of ecological, social and economic value—has the potential to provide suitable mechanisms for this holistic transformation. Its sectors and industries have already demonstrated strong innovation potential through the use of science, enabling and industrial technologies, as well as local and tacit knowledge (De Besi and McCormick 2015). The bioeconomy can bring about positive change through knowledge-based and targeted innovation.

By implementing bioeconomy solutions along established and novel bio-based value chains and webs (see ▶ Chap. 4), the nutritional, energetic and material needs of our society can be fulfilled through the efficient use of renewable resources (i.e. biomass) in closed cycles. The transformation to a bioeconomy can aim to address several global challenges arising from population growth (e.g. food security, health and energy security) or in response to risks resulting from climate change (see ▶ Chap. 1). At the same time, the transformation to a bioeconomy can be seen as a tool to promote technological innovation (Dietz et al. 2018; Bringezu et al. 2020; Muscat et al. 2021).

The most important resource for a bioeconomy is biomass. The increasing demand to shift from a fossil resource base to a renewable resource base for various uses (food, feed, fuel, fiber) may result in additional environmental pressures and competition for resources (e.g. land, water, labour). How the production and consumption pathways of a bioeconomy develop, very much depends on the regional context and conditions (Pyka et al. 2020). The bioeconomy aims to link economic sectors and actors that produce and use biomass (e.g. farmers, traditional and novel food industries) at different levels (regional and interregional), resulting in a variety of products, services and relationships (see ▶ Chap. 4).

In doing so, the bioeconomy has to navigate numerous trade-offs, balancing ecological sustainability with economic viability and social acceptability. This includes, amongst other things, managing competing land uses, such as agriculture for food versus bioenergy crops, and addressing the potential impacts on biodiversity and ecosystem services (see ▶ Chaps. 40 and 41). In addition, the bioeconomy must adapt to external factors such as climate change, economic shifts and political developments that can influence resource availability (e.g. biomass, investments) and facilitate or hinder the transition process.

The plurality of understandings and interpretations of the term ‘bioeconomy’ (see ▶ Chap. 2 on the development of the concept) has resulted in the lack of a common understanding of what it actually means (Bracco et al. 2019). This indicates that the term ‘bioeconomy’ requires fundamental discussion, contestation, adaptation and evolution over time.

The question arises as to what impact the various bioeconomy transformation pathways will have when they are comprehensively evaluated from different perspectives (Egenolf and Bringezu 2019). Depending on the underlying regional conditions and assumptions, both opportunities and potential conflicts and risks are possible (Dietz et al. 2018). This implies that a bioeconomy transformation should have no fixed contours but should follow overarching principles that serve as guard rails or fixed stars for their design and development. While this concept is a good starting point, it must be elaborated on to reflect our reality and ensure that it can achieve the goals of mitigating and adapting to climate change and protecting nature as part of a just-transition (EU Bioeconomy Youth Ambassadors 2024). A sustainable (regional) bioeconomy should aim at the provision of a good life for all within regional and global planetary boundaries.

In the following sections, we propose principles and provide an outlook on how to create the conditions necessary for a sustainable bioeconomy, placing the concept in a broader context. The principles serve as an overview of ‘universal’, general conditions or descriptive elements for achieving a bioeconomy transformation. They act as a kind of DNA of the bioeconomy and should guide the transition and innovation process to promote its facilitation. The principles provide an overview of the role of the various dimensions in the development and implementation of the bioeconomy at different levels and are intended to ensure that a correctly implemented bioeconomy can serve society, for example in line with the Sustainable Development Goals (SDGs). In the context of the bioeconomy, these principles are:

1. *Sustainability*: Ensuring that bioeconomic practices are sustainable by considering long-term environmental impacts, resource regeneration, and ecosystem health.
2. *Multifunctionality*: Fostering the capacity to fulfil multiple purposes simultaneously, including delivering economic value, supporting environmental sustainability, and providing social benefits.
3. *Circularity and cascading resource use*: Promoting the reuse, recycling and regeneration of resources to create closed-loop systems that reduce waste and increase resource efficiency.
4. *Inter- and transdisciplinarity*: Combining knowledge from different fields to address challenges and opportunities comprehensively while engaging diverse stakeholders, including policymakers, industries, communities, and researchers.
5. *A holistic systems thinking approach*: Understanding and evaluating bioeconomy with its interdependencies and contextualities, for example, the entire life cycle of a product from resource extraction to disposal within socio-economic frame conditions.

3.1 Sustainability and Multidimensionality

The concept of sustainability in the context of productive economic systems has its origins in forestry—to preserve the value of the forest and ensure its future usability: only as many trees should be felled as can grow back. Translated into an overall concept this means that sustainability aims to conserve essential natural resources, promote economic growth by better protecting the environment whilst safeguarding prosperity and social progress. As explained in ▶ Chap. 2, the broader application of the term sustainability was highlighted in the Brundtland Report of 1987, officially known as 'Our Common Future', which emphasized the need for sustainable development practices globally (United Nations Brundtland Commission 1987).

> ***Sustainability*** is the practice of meeting current needs without compromising the ability of future generations to meet their own needs (United Nations Brundtland Commission 1987). It encompasses maintaining a balance between economic growth, environmental protection and social well-being.

Central to the concept of sustainability is the 'triple bottom line'. Often summarized as 'people, planet, and profit', the triple bottom line, emphasizes that true sustainability requires a balanced consideration of economic viability, social equity and environmental health (see ◘ Fig. 3.1). This means operating in ways that enhance societal wellbeing, conserve and protect natural resources, and remain financially profitable. By integrating these three dimensions, the triple bottom line encourages more responsible and ethical decision-making, ultimately aiming for a harmonious coexistence of human activities and the Earth's ecosystems.

Do you want to learn more about the history of sustainability? Take a look at ◘ Supplementary Video 3.1, a video from our MOOC "Concepts of Sustainable Bioeconomy" (2021).

In simple terms, the concept of sustainability implies finding better or the best solutions (whether ecological, economic or social) to challenges associated with complex problems that relate to a specific temporal and geographical scale (Santillo 2007). This means that the term is highly dependent on the context in which it is applied and the perspective on which it is based. Sustainability can be defined and used in broad or narrow terms (e.g. weak or strong sustainability), but a useful application must specify the context as well as the temporal and spatial scales being considered (Brown et al. 1987).

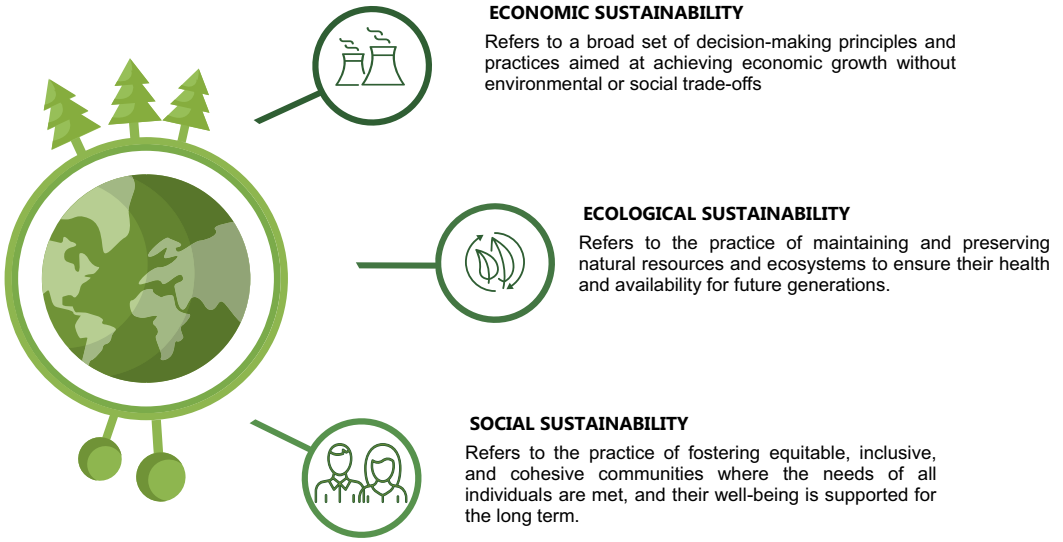


Fig. 3.1 Sustainability dimensions: triple bottom line

> ***Weak sustainability*** assumes that natural capital and manufactured capital are essentially substitutable and considers that there are no essential differences between the kinds of well-being they generate. The total value of the aggregate stock of capital, should be at least maintained or ideally increased for the sake of future generations.
>
> ***Strong sustainability*** disagrees with the interchangeability of natural and manufactured capitals as some elements of natural capital are critical due to their unique contribution to human well-being. Critical natural capital can be conceptualized as ecosystem services provided by natural capital. This highlights the need to maintain the ecological functioning of natural systems in order to preserve the capacity of natural capital to provide those services which are critical to human existence and well-being (Brand 2009; Pelenc and Ballet 2015).

Our socio-economic systems are based on natural resources (see ► Chap. 1). With the help of labour and capital, raw materials are transformed into goods that serve to satisfy people's needs. The impacts of our current economic system on the environment are so extensive that the risk of irreversible changes and damage to our ecosystems and human wellbeing is increasing (Steffen et al. 2015; Richardson et al. 2023). Forces of change such as technological advances, geopolitical dynamics, and climatic shifts will inevitably disrupt the cycles of material and energy flows. Therefore, achieving sustainability will arguably require the development of resilient, adaptive systems and vice versa (Fiksel and Bakshi 2023).

We need to develop systems that are capable of handling unexpected changes. These systems must be regenerative and diverse, capable of relying on their capacity, and evolve with shocks. This concept of *resilience* is crucial to sustainability (Cascio 2009). This is where the bioeconomy comes into play. Bioeconomy systems offer an alternative to traditional, fossil-based systems by providing an approach that can be aligned with these principles to promote a system that is sustainable, resilient, adaptive, regenerative and able to thrive amidst changes.

The bioeconomy presents a pathway to reduce or eliminate emissions while ensuring positive contribution to (among others) biodiversity, ecosystem services, and social well-being. By integrating bioeconomic strategies,

we can strengthen efforts in climate change mitigation and adaptation, foster sustainable economic development, and address challenges within our current socio-economic systems. The bioeconomy contributes to mitigation through clean energy provision, carbon sequestration (capturing and storing carbon dioxide from the atmosphere), and the creation of carbon sinks, such as afforestation. Additionally, by promoting climate-resilient agricultural systems and sustainable practices like conservation agriculture, agroforestry and organic farming, the bioeconomy plays a significant role in adaptation.

However, an increasing demand for bio-based resources raises important social-ecological sustainability concerns (Pyka et al. 2020). This includes the challenges of how to use water and land sustainably and effective to produce biomass as well as mitigating the impacts on the ecosystem and its biological diversity (Pfau et al. 2014; Dietz et al. 2018; Gawel et al. 2019). Biodiversity, the variety and diversity of all life forms on earth, contributes to the effective functioning of natural systems and supports ecosystem services such as clean water, fertile soils and climate regulation, on which the environment depends (Locke et al. 2021). It is also the source of the biological resources on which the bioeconomy depends (see ▶ Chap. 40). Therefore, bioeconomic innovations must focus on developing resource-efficient technologies and methods to increase productivity in agriculture, forestry, and aquaculture, while ensuring resource sufficiency, promoting resource consistency and preserving the Earth's carrying capacity and biodiversity.

Excursus 3.1: Resource Management

A successful shift towards sustainability requires meeting the three key aspects of resource management: efficiency, sufficiency and consistency. *Resource efficiency* means gaining more benefit from each unit of natural resource used. This ties into *resource sufficiency*, which focuses on reducing the overall consumption of primary raw materials. Additionally, *resource consistency* or replacing non-renewable resources with renewable ones, is crucial for achieving a sustainable future (Zukunftsagentur Rheinisches Revier 2021).

Do you want to learn more about sustainability strategies, efficiency, effectivity/consistency, or sufficiency? Take a look at ◘ Supplementary Video 3.2, a video from our MOOC "Concepts of Sustainable Bioeconomy" (2021).

A sustainable bioeconomy requires careful design and development, guided by conscious planning and comprehensive assessment (Wellisch et al. 2010, p. 283). Applying ecologically sound principles, such as syntropy, agroecology, land restoration and sustainable intensification, is crucial to designing bio-based systems that avoid negative impacts on ecosystems. To ensure positive contributions to sustainability, it is equally important to address social, economic and technological dimensions alongside ecological considerations (Schindler 2021). The resulting *multidimensionality* ensures that the bioeconomy is both inclusive and comprehensive, tackling key challenges across interconnected areas.

Multidimensionality in a sustainable bioeconomy acknowledges the various dimensions—environmental, economic, social and technological—that need to be considered to achieve sustainability.

- Environmental: water management, sustainable land use, climate change adaptation and mitigation, biodiversity conservation and promotion
- Social: food security, inclusiveness, integration of traditional knowledge, fair access and equity
- Economic: innovation, value addition, job creation, income diversification, value chain development
- Technological: biotechnological advances, novel biomass sources, new processes and products, biorefinery approaches, carbon capture and utilization (CCU), AI and big data

The transition to a sustainable bioeconomy entails the transformation of production towards the creation of environmental, social and economic value. It has no fixed contours, but takes shape through the process of weighing up opportunities and risks in the local context. The concept of sustainability must therefore be a guiding principle for the transformation to a bioeconomy (Gawel, Pannicke and Hagemann 2019). A bioeconomy must adopt an integrated, long-term perspective that connects all dimensions of sustainability. There is a need for both new technologies that enable a more sustainable use of bio-based resources, and assessment methods that facilitate a robust and forward-looking impact assessment of existing and new bio-based solutions (see ▶ Chap. 41).

This requires a willingness to transform business models and processes in a sustainable way. From a global perspective, the bioeconomy could trigger positive distribution effects (and thus contribute to intra- and intergenerational justice) and create a renewable resource base that would not be limited by the finite nature of fossil resources. *A sustainable bioeconomy must hence ensure that no more bio-based resources are consumed than can be regrown.*

- **Practical Implications:**
- Integration and promotion of sustainable development in all dimensions (economic, social and environmental) of the bioeconomy
- Advancement of efforts to mitigate and adapt to global climate change
- Definition and application of a comprehensive set of environmental, social and economic sustainability goals and criteria
  - SDGs = global framework of goals for holistic sustainable development and important tool to measure and create the prerequisites for a sustainable transition of our socio-economic systems (Zeug et al. 2019)
- Comprehensive, rigorous and transparent assessment procedures are required to ensure that the bioeconomy can be economically, ecologically and socially sustainable
  - Life-cycle approaches can be used to examine key impact categories and indicators, assessing the environmental and social impacts (e.g. carbon, water and biodiversity footprints, social impact assessments), as well as the ultimate effects of these on all three key sustainability pillars (e.g. Life Cycle Sustainability Assessment) (see ▶ Chap. 41).
- Increasing sustainable practices and consumption in the bioeconomy through various methods including sustainable intensification (see section agricultural production) and resource management

3.2 Multifunctionality

A bioeconomy can deliver multiple and diverse outputs. For example, a multifunctional system based on agricultural biomass might produce food, fibre, and bioenergy while also enhancing biodiversity, sequestering carbon, and supporting rural livelihoods. Similarly, a multifunctional biorefinery (see ▶ Chap. 17) could convert different types of biomass into a range of products, including biofuels, bioplastics, and pharmaceuticals, thereby maximizing resource efficiency and economic value.

In the bioeconomy, ***multifunctionality*** refers to the ability of biological resources and systems to simultaneously serve multiple purposes, such as providing economic value, supporting environmental sustainability and offering social benefits. This concept emphasizes the integrated and diverse use of resources, fostering cross-disciplinary collaboration to maximize benefits while minimizing negative impacts on ecosystems.

Promoting multifunctionality in a bioeconomy means designing systems and practices that harness the full spectrum of biological potential. This approach can lead to more resilient and adaptive bioeconomy systems, as it diversifies the benefits derived

from biological resources and reduces dependence on individual outputs. By leveraging multifunctionality, a bioeconomy can contribute to a more integrated approach to resource management and development, while ensuring that it meets multiple sustainability objectives—economic, environmental, and social (Lewandowski et al. 2024). Multifunctionality in the bioeconomy can be explained using the example of miscanthus, a high-yielding perennial grass. This grass can be used as a feedstock for a diverse range of applications (bioenergy, biomaterials) (◘ Fig. 3.2 right) in various sectors, while also providing multiple ecosystem services (◘ Fig. 3.2 left) while contributing to sustainability (carbon sequestration, improving soil health and promoting biodiversity).



◘ **Fig. 3.2** The perennial biomass grass miscanthus during the time of maximal biomass growth in August. Flowers (picture top right) are developing in autumn. (© Moritz von Cossel)

Excursus 3.2: Miscanthus

Miscanthus is a perennial, rhizomatous biomass grass with C4 photosynthetic pathway (see ▶ Sect. 5.1 for the process of photosynthesis). These physiological features, amongst others, make miscanthus a crop that has a high potential for contributing to multifunctional agricultural production systems:

Under favourable conditions, the C4 photosynthetic pathway can achieve up to 24% radiation efficiency, compared to 15% for C3 plants, leading to more efficient use of water and nitrogen, and ultimately higher land-use efficiency and yields in C4 crops.

In the perennial miscanthus cropping system, plants are established once over a period of 20–30 years. The soil is only cultivated in the first year, with subsequent years focusing on harvesting regrowing biomass. The undisturbed soil supports biodiversity, prevents erosion, and allows carbon to accumulate.

Miscanthus stores nutrients over the winter in rhizomes (underground stems), with 20–50% of essential nutrients (N, P, K, Mg) being translocated from the aboveground stems to the rhizomes. This internal nutrient cycling reduces fertilization requirements and minimizes envi-

ronmental impacts, including greenhouse gas emissions, nitrate leaching and eutrophication (Fig. 3.3).

Miscanthus is widely used for bioenergy production. Its biomass can be burned directly or co-fired with coal to produce electricity and heat. For energy purposes, miscanthus biomass is either harvested dry in early spring, after plant nutrients have been translocated to the rhizomes, or harvested green in late autumn for use as biogas feedstock (Kiesel and Lewandowski 2017). Enzymatic hydrolysis of its lignocellulosic biomass can yield ethanol for use as a biofuel (Lask et al. 2018) (Fig. 3.4).

Research on miscanthus-based biochemicals, such as HMF (hydroxymethylfurfural) is underway, for example at the biorefinery of the University of Hohenheim (Götz et al. 2023). Miscanthus biomass can also be used to produce biomaterials such as bioplastics, composites, paper and building materials. It is a valuable feedstock for natural fibre-reinforced composites in the automotive and construction industries.

On-farm applications include its use as bedding for poultry and horses. When used bedding for turkeys, its high water adsorption capacity allows it to last an entire cycle, unlike straw, which has to be changed several times. For horses, it offers an alternative to straw, providing a dust-free option that is particularly beneficial for horses with allergies (Lewandowski et al. 2022). In both cases, miscanthus bedding not only fulfils its primary purpose but also promotes animal health. Miscanthus contributes to carbon sequestration and climate change mitigation by taking in CO_2 through photosynthesis and storing it as biomass carbon. It's deep rooting system and rhizomes transfer this carbon to the soil as organic matter, enhancing soil carbon storage. Miscanthus can also sequester carbon in long-lasting materials, such as building products, until they re-enter the CO_2 cycle at the end of their use period. When used as biofuel, it can help to reduce greenhouse gas emissions by replacing fossil fuels (Fig. 3.5).

In addition to its environmental benefits, miscanthus contributes to soil improvement and erosion control. Its dense and perennial root system helps stabilize the soil and reduce the risk of soil erosion, particularly on degraded or marginal land. It also enhances soil fertility by increasing organic matter and improving soil structure and water retention, both of which are crucial for future crop growth. Another valuable function that miscanthus can provide is floodwater control. Strip cultivation alone can be very effective in breaking or diverting floodwater flows. Finally, the perennial nature of miscanthus and the fact that the fields remain undisturbed for long periods of time promote biodiversity by providing habitats for wildlife, including birds and insects, thus contributing to biodiversity conservation. In addition, as a low-input crop, miscanthus cultivation requires only minimal use of fertilizers and pesticides, helping to reduce environmental pollution and promote sustainable farming practices.

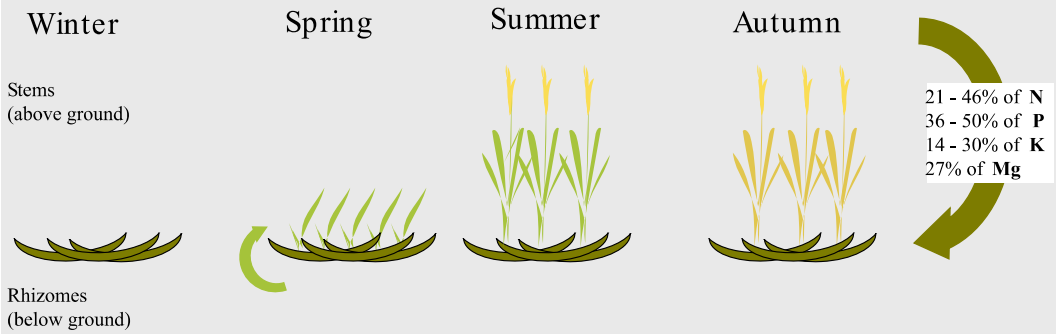


Fig. 3.3 The plant-internal cycle of the major plant nutrients nitrogen (N), phosphorus (P), potassium (K) and magnesium (Mg) in miscanthus growth over the course of the year. Nutrients are stored in the rhizomes and feed the new sprouting stems in spring. In autumn the process is reversed and nutrients are mobilized from the above ground to the below ground rhizomes before the biomass is harvested

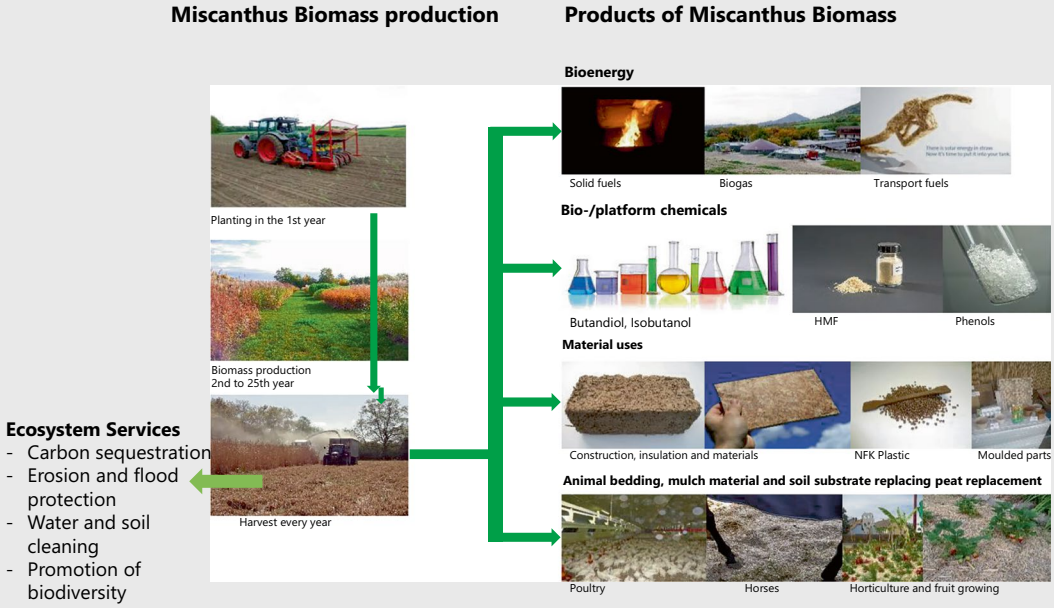


Fig. 3.4 Miscanthus delivers biomass for multiple bio-based products simultaneously with different ecosystem services

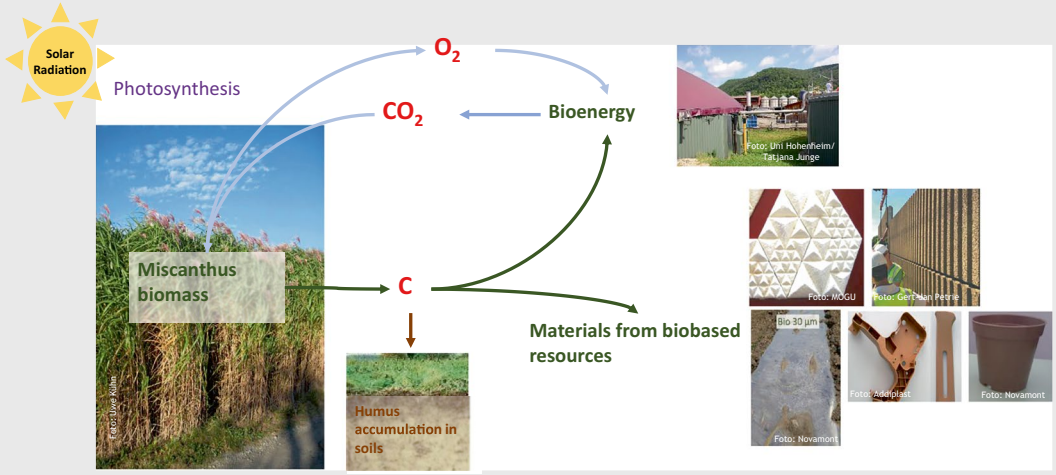


Fig. 3.5 How miscanthus biomass production delivers biomass for different products and reduces atmospheric CO_2 at the same time

- Prioritize multifunctional solutions that serve multiple purposes and can overcome trade-offs
- Consideration of multiple valorisation pathways and context conditions in the design and development of novel bio-based systems (see ▶ Chap. 4)

3.3 Circularity and Cascading Resource Use

The concept of circularity aims to transform the current, largely linear economic system into a sustainable, regenerative one (Carus and Dammer 2018). By minimizing waste and resource consumption through eco-design, recycling, and reuse, circularity seeks to close material loops, preserve the functionality of components and materials, and maintain their value over time (European Environmental Agency 2016). Circularity focuses on the entire value chain from product design to the selection and production of raw materials, logistics, consumption and the integration of the product at the end of its life cycle into new value creation (Zukunftsagentur Rheinisches Revier 2021).

The concept of circularity offers various social, economic and environmental benefits and is considered a crucial component for the sustainable transition of our economic system (European Environmental Agency 2016; Carus and Dammer 2018; Muscat et al. 2021; Stegmann et al. 2020). In an ideal circular economy, raw materials are transformed into goods that, after use, become waste that can be reused, closing the loop of resource consumption (McDonough and Braungart 2002). The benefits of this model are especially evident in a bioeconomy, where the circular flow extends to biological resources and nutrients.

The term ***circular economy*** describes a regenerative system in which resource input and waste, emissions and energy leakage are minimized by slowing down, closing or narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacture, refurbishment and recycling (Geissdoerfer et al. 2018).

The principles of circularity align seamlessly with the renewable nature of a bioeconomy transformation, as both aim to integrate economic, environmental and social goals to achieve sustainability targets (D'Amato et al. 2017; Carus and Dammer 2018; Klauer and Schindler 2020). A circular bioeconomy operates within a circularity framework, using biomass and bio-based waste streams as a key element to produce various bioproducts, biochemicals, and bioenergy in biorefineries. The bio-based circular economy approach focuses on the utilization of biomass and bio-based waste streams to produce versatile products and energy sources.

Integrating circularity principles into the bioeconomy can enhance the efficiency of biomass use and generate new value from waste streams (Klauer and Schindler 2020; Muscat et al. 2021). The goal of incorporating these principles is to optimize the use of natural resources and reduce waste through the creation of new value channels. Various practices, such as nutrient recovery, paper recycling, and biogas production bridge multiple sectors including water, sanitation, food and construction. This integration, or multisector coupling, has become a fundamental aspect of the circular bioeconomy (Schipfer et al. 2024).

However, in our current economic system, the use of bio-based resources has generally been neither circular nor resource-efficient.

Despite the promising opportunities and environmental benefits, a closer examination reveals that this approach also presents several challenges.

Bio-based resources, derived from plants that capture carbon from the atmosphere, contribute to the carbon cycle by returning carbon to the soil or atmosphere after the products made from these plants are used

The term *circular bioeconomy* describes a framework for an economy that is restorative and regenerative by design. The model combines the sustainable use of renewable biological resources with circularity principles to minimize the generation of waste while increasing resource-use efficiency. Preservation of biodiversity and regeneration of materials is prioritized, and the reliance of fossil fuels is reduced. By driving innovation in bio-based, recyclable and biodegradable solutions, the circular bioeconomy promotes closed-loop systems that combine economic growth with environmental sustainability, addressing challenges such as climate change and resource scarcity.

and discarded (Carrez and Van Leeuwen 2015).

It is not always possible to fully recycle many types of waste. Achieving endless recycling (100% recycling) is often both economically unfeasible and technologically impractical (Fritsche et al. 2020). Moreover, non-renewable resources, such as minerals, metals, and rare-earth elements, remain essential to our economic system, even with the most advanced technologies (e.g. in electronics production). Biomass flows differ from those of minerals and metals due to the unique characteristics of biomass, such as biodegradability, which limits storage and reuse options and presents specific environmental and societal challenges at the disposal stage. Biomass is valued for its diverse properties such as nutritional content, energy value, strength, water content, and sensory qualities which complicate its circular use.

Thermodynamic laws limit the potential for a perfectly closed-loop system. For example, recycling processes often degrade materials and consume energy, necessitating the addition of new resources to maintain the cycle (Corvellec et al. 2022; Giampietro and Funtowicz 2020). This gradual degradation, known as 'dissipative loss', complicates efforts to achieve ideal circularity. Moreover, rebound effects, such as increased consumption resulting from resource efficiency gains, can offset environmental benefits (see Excursus 3.3).

Cascading resource use is a strategy that aligns closely with the principles of the circular bioeconomy. Cascading aims to optimize the value of biomass over time in terms of economic, environmental and social aspects, ideally addressing all three pillars of sustainability.

For example, the European Commission prioritizes the cascading use of wood-based biomass, starting with high-value applications and ending with energy generation as the final step. They define the cascading use of wood-based biomass with the following order of pri-

Excursus 3.3: Rebound Effect

The '*rebound effect*' is an umbrella term for a variety of economic mechanisms that reduce the 'energy savings' from improved energy efficiency (Lange et al. 2021).

The rebound effect in a circular economy refers to unintended consequences of improvements in resource efficiency that lead to increased overall consumption. For example, cost savings from efficient practices may result in more production or use of resources, offsetting the environmental benefits. The two main rebound effects in circular economies are (Schultz et al. 2024):

1. Imperfect and/or insufficient substitution between virgin and recycled or reused materi-

als: Rebound occurs when re-circulated products cannot effectively compete with primary production products, leading consumers to buy more disposable items, thereby increasing the overall environmental impact.
2. Re-spending or income effects: Rebound occurs when consumers purchase additional goods and services because the substitution of costly resources lowers prices. This increase in purchasing power leads to a strong positive income effect that overcompensates for the initial substitution effect.

orities: 'wood-based products; extending their service life; re-use; recycling; bioenergy; disposal'. (European Commission 2022).

In a circular bioeconomy, the emphasis shifts toward the sustainable and resource-efficient utilization of biomass through integrated, multi-product systems, such as biorefineries (see ► Chap. 17). This approach not only maximizes the value derived from biomass but also ensures the processing of residues and wastes, thereby closing material loops and enhancing sustainability.

Cascading resource use or simply ***cascading*** refers to the continuous use of resources for various purposes, optimally through different material reuse phases. The concept of cascading is described as a strategy to preserve the 'added value' of products for the longest time possible. Similar to the circular bioeconomy, cascading promotes the consecutive circulation of resources, thus increasing resource-use efficiency (Blomsma and Brennan 2017; Campbell-Johnston et al. 2020).

These efforts are mainly driven by technological innovations in areas such as biotechnology, precision agriculture and other innovative manufacturing technologies, while social, organizational and institutional innovations (e.g. waste use policy frameworks, new business models) complement efforts to achieve the minimization and utilization of residues. Cherubini (2010) and others have contributed to the definition of the biorefinery concept as an integrated production approach for the full utilization of biomass for the production of a wide spectrum of products and services, while minimizing waste and emissions from the processing and conversion of products (see ► Chap. 17).

Biorefining is the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials and chemicals) and energy (fuels, electricity and heat). A biorefinery is an infrastructure facility or cluster of facilities where various conversion technologies (physical or mechanical, thermochemical, biochemical, chemical) are integrated to produce sustainable bio-based products (e.g. biofuels, biochemicals, bio-based materials and other high-value products).

This concept plays a key role in the optimization of biomass conversion to achieve the goals set for the bioeconomy concept (Ubando et al. 2020).

To ensure a sustainable regional biomass supply, address potential shortages, and optimize resource use, bioeconomy policies emphasize advanced circularity models. These models prioritize resource efficiency, recycling, the utilization of waste and side streams, and the promotion of sustainable consumption practices. The EU Waste Framework Directive provides a foundation for these efforts, emphasizing the waste hierarchy as a guide for minimizing environmental impacts and maximizing resource efficiency.

The bio-products value pyramid further illustrates the importance of prioritizing high-value uses for biomass. Lower-value applica-

tions, such as combustion for energy, require large volumes of biomass but deliver limited benefits. Conversely, higher-value applications use smaller quantities of biomass while yielding greater economic and environmental gains. The cascading steps should therefore focus on maintaining resource quality by adhering to the bio-products value pyramid (see ◘ Fig. 3.6.) and, where appropriate, the waste hierarchy.

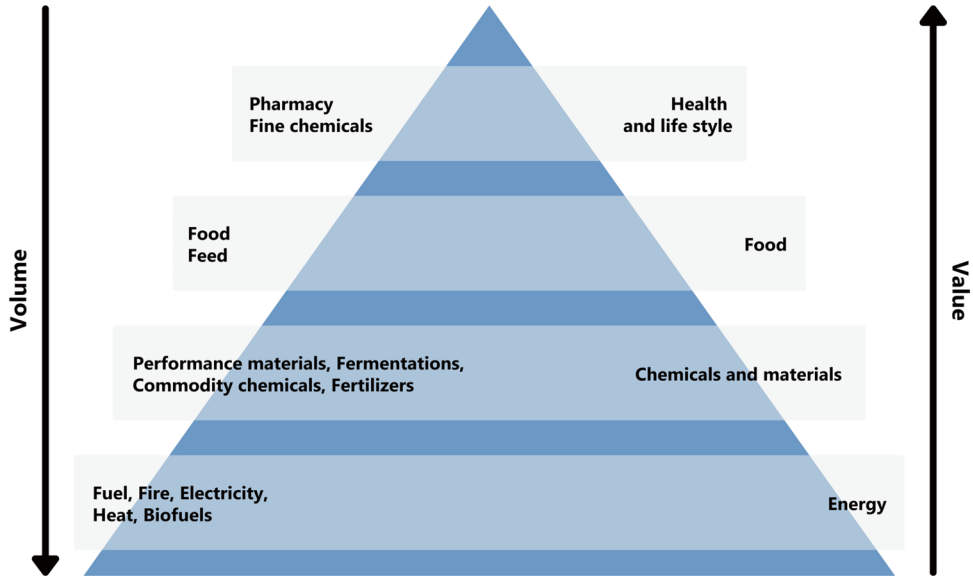
The ***waste hierarchy*** serves as a priority order in waste prevention and management legislation and policy (see also ► Chap. 13). It is a fundamental element of EU waste policies and laid down in the EU Waste Framework Directive (Directive 2008/98/EC). Its objectives are:

1. To minimize the negative impacts of waste generation and management.
2. To enhance resource efficiency.

Circularity principles and the bioeconomy share a common vision of achieving sustainability by combining economic, environmental and social goals. However, realizing this vision requires addressing challenges such as resource limitations, technological constraints, and rebound effects. By fostering innovation and promoting integrated strategies such as cascading and biorefineries, the circular bioeconomy can become a cornerstone of sustainable development, balancing the needs of a growing population with the imperative to conserve natural resources.

Excursus 3.4: Bio-Product Value Pyramid

The bio-products value pyramid (◘ Fig. 3.6; see also ► Chap. 17) illustrates the diverse value-added applications of biomass along the production chain. The pyramid is structured to show that lower-value uses are positioned at the base, with higher-value products and applications located towards the top. At the base, biomass is used for combustion to generate heat and electricity, representing the lowest value. Moving up the pyramid, the value of products increases while the required biomass volume decreases, as higher-value applications involve smaller quantities of biomass but deliver greater economic and environmental benefits (see also ► Chap. 17).



◘ **Fig. 3.6** Bio-products value pyramid

► Example: 'KeRaus—Analysing the closed-loop recycling of renewable raw materials from secondary urban sources'

To achieve the goal of closing loops within defined spatial boundaries, a screening of bio-products obtained from biorefineries is crucial. In urban areas, there is a concentration of raw material and re-source flows to supply these very densely populated areas with resources, goods and products. Their consumption generates enormous amounts of biomass residues and waste products, including both solid and liquid waste, and wastewater. A bioeconomic coupling and cascading use of these residue and waste streams from urban areas for the production of a wide range of bio-based materials and products (e.g. fertilizers) forms the basis of a circular and sustainable urban-rural resource metabolism in the sense of the circular economy (Trenkner et al. 2025).

The project 'KeRaus—Analysing the closed-loop recycling of renewable raw materials from secondary urban sources' characterizes and evaluates the practical implementation feasibility of fertilizers produced in biorefineries from organic waste, green waste and sewage sludge streams, operating within a 100-km radius of the city of Stuttgart. In Stuttgart, 64,000 t of organic waste and green waste, and 15,000 t of sewage sludge (dry matter) are produced every year. These biomass waste streams contain many untapped valuable residues (such as minerals for plant nutrition), which could potentially be processed and recycled. Recycling the nutrient-rich waste streams through bioeconomic conversion pathways and technologies to produce fertilizers could benefit both the urban and rural areas. Agricultural producers and stakeholders are supported through a continuous supply of fertilizer, food security is ensured sustainably, and environmental impacts of fertilizer production are minimized. By providing new bioeconomic value chains for the use of biomass residue and waste streams, the urban and rural areas of Stuttgart can be optimally linked. The attributes re-quired of the fertilizers produced in the biorefineries (quantity, properties, quality criteria and com-position) are identified and determined based on demand from agricultural stakeholders. The project provides recommendations for action to improve processes within the biorefineries in order to develop valuable products. Finally, optimal bioeconomic pathways for the valorization of municipal waste as recycled fertilizer (see ► Chap. 14) for use in agricultural processes are demonstrated. This closes the resource loop between rural and urban areas in terms of important plant nutrients.

Overall, KeRaus provides a clear answer on how much fertilizer is currently needed and how much can be replaced by recycled fertilizer, and a clear analysis of the potential for utilizing urban waste from Stuttgart. Figure 3.7 graphically illustrates the structure and goals of this research project. Rural and urban areas are shown separately: the rural areas focus on agricultural production, resulting in food streams that supply the urban areas. The urban areas are characterized by food consumption, generating waste streams. By recycling waste to produce recycling fertilizer, the nutrient loop between the two areas can be closed. ◄

Practical implications:

- Advance the efficient and circular use of biological resources
- Set spatial boundaries
  - Identify input and output streams to set spatial boundaries
  - Characterize waste and residue streams for the identification of valorisation pathways
  - Identify demand for bio-based products to guide the choice of applications with high-added value
- Screen and develop biorefinery technologies for the production of products from waste and residue inputs, for which there is demand
- Evaluate outputs and give recommendations for the implementation of bio-based products derived from secondary resources

3.4 Inter- and Transdisciplinarity

A bioeconomy is based on the collaboration of agricultural, natural, economic and social sciences, among others, and encompasses a wide range of activities along a multitude of

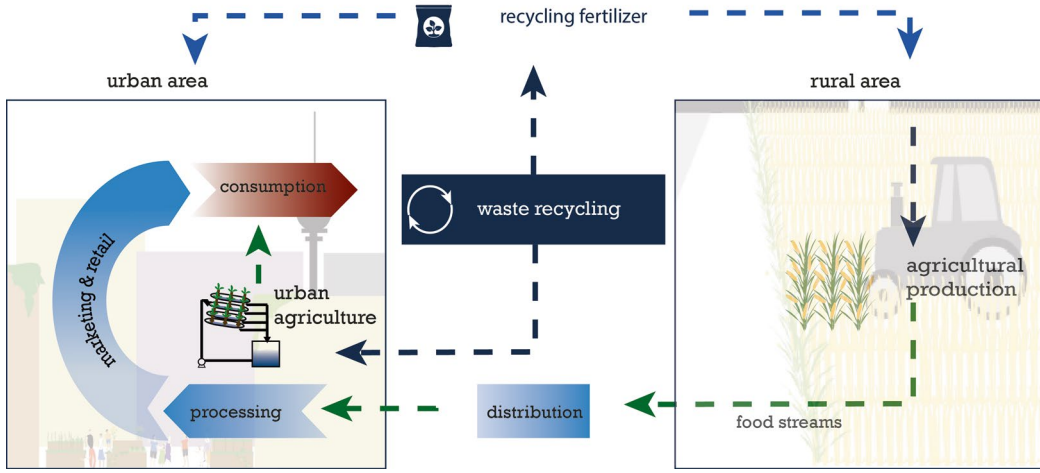


Fig. 3.7 Schematic illustration of the closed loop of agricultural waste and residue streams to produce recycling fertilizer for agricultural processes in urban and rural areas. (© Marielle Trenkner)

diverse value chains (Hasenheit et al. 2016; FAO 2018; Lewandowski 2018). A societal transition to a more sustainable form of production and resource use within the bioeconomy paradigm requires the successful integration of scientific and practical knowledge, as well as the cooperation of a numerous actors from various societal subsystems. The bioeconomy combines multiple sectors such as agriculture, forestry and biotechnology as well as different actors (e.g. farmers, processors, public sector, NGOs, civil society). The interplay between these sectors and interconnected actors can be understood as the governance system (See ▶ Sect. 29.1) of the bioeconomy, a network in which all interconnections shape, and can change with, the development of a bioeconomy.

The bioeconomy aims to address so-called 'wicked problems', which refer to social-ecological challenges of very high complexity (See ▶ Sect. 38.1). The bioeconomy operates at the interface of science and society. It requires the integration of a plurality of different types of knowledge (e.g. scientific, traditional, systems, normative and transformative) and expertise, while being dispersed across different institutions, locations and disciplines. The bioeconomy research community therefore recognizes the need for inter- and transdisciplinary approaches to support the transition to a sustainable bioeconomy (e.g. Friedrich et al. 2021).

Interdisciplinarity in the bioeconomy means an interchange and dialogue between academic disciplines, whereas transdisciplinarity aims at contextualization and integration of different perspectives within a broader context (Knierim et al. 2018; Zeug et al. 2020).

Despite the difficulties, an inter- and transdisciplinary approach can help maintain a systemic view and look at problems from a range of perspectives. For a bioeconomy, inter- and transdisciplinary research can therefore be a starting point to gain a better understanding of social-ecological problems and contribute to their solution (Zeug et al.

Interdisciplinarity refers to the integration and synthesis of ideas, methods and approaches from different academic disciplines to address complex issues, solve problems, or create new understanding that would be difficult or impossible to achieve within the confines of a single discipline. Interdisciplinarity involves different disciplinary approaches to research in a conceptually coordinated way, where the disciplinarily guiding assumptions and research concepts ('worldviews') are made explicit and interrelated. In an interdisciplinary approach, the 'facts and findings' of each discipline are critically evaluated in the light of the 'facts' of the other disciplines, and an attempt is made to integrate discipline-specific knowledge into a larger whole (Schmidt 2008).

Transdisciplinarity expands the scope of research into another dimension of study. In addition to focusing on real-life problems, it seeks to integrate lay or non-academic knowledge with scientific knowledge. Transdisciplinarity is a specific form of interdisciplinarity in which the boundaries between and across disciplines are transcended and knowledge and perspectives from different scien-tific fields as well as from non-scientific sources are integrated (Hirsch Hadorn and Pohl 2010). Transdisciplinary research aims to go beyond disciplinary worldviews to include non-academic perspectives and expertise from various stakeholders (Pohl et al. 2021).

2021). This entails an understanding of the system, its components and interrelationships that lead to today's challenges and outcomes (positive and negative), and also the desired state of the system, as framed by society and embedded in a larger ecological system. The definition of the desired or target state requires the integration of stakeholder expectations and needs, as well as a comprehensive view based on different research perspectives and disciplinary angles.

In the context of the bioeconomy, approaching research and development through inter- and transdisciplinary collaboration is crucial for generating knowledge that addresses complex, real-world challenges. To develop practical and implementable solutions—such as innovations that promote sustainable resource use and circular economy models—it is necessary to move beyond traditional disciplinary boundaries. This involves integrating knowledge from diverse fields such as biology, economics and engineering, as well as engaging non-scientific perspectives, including insights from industry stakeholders, policymakers and local communities. By involving societal stakeholders, research can be more effectively directed towards solving real-world problems, such as reducing waste, increasing biomass production and ensuring long-term ecological sustainability. Ultimately, the integration of these diverse perspectives ensures that bioeconomic solutions are both scientifically sound and socially relevant.

▶ Chapter 37 provides an in-depth exploration of interdisciplinarity and transdisciplinarity, explaining how these concepts transcend traditional academic boundaries. This chapter focuses on the justification for inter- and transdisciplinary research in bioeconomics (▶ Sect. 37.1), the characteristics of the inter- and transdisciplinary research process (▶ Sect. 37.2), and methods and tools to make collaboration effective and efficient (▶ Sect. 37.3). It also highlights the roles and responsibilities that researchers have when engaging in inter- and transdisciplinary research (▶ Sect. 37.4).

- **Practical Implications:**
  - Being inclusive and equitable in bioeconomy transformation by upholding the rights of all people and promoting gender equality and the active participation of stakeholders involved are key principles
  - For interdisciplinary cooperation, engage with research colleagues so that disciplinary perspectives are mutually considered and knowledge is jointly created and integrated
  - To practice transdisciplinarity, include all societal actors when

– aligning goals and perspectives
– developing new solutions
– implementing and evaluating solutions.

Be aware that participation of actors can be achieved through different formats and means.

3.5 A Holistic Systems Thinking Approach in the Bioeconomy

A bioeconomy involves processes and relationship along the production, supply and conversion of biomass into a wide range of products and services. A variety of natural and societal elements are part of the socio-economic and environmental systems in which the bioeconomy operates. Accordingly, a bioeconomy can be described as a social–ecological systems that combines people, technology, biological processes and ecological systems and their services to satisfy the needs of people in a specific geographical territory (Wohlfahrt et al. 2019; Vargas-Carpintero 2025; Schlecht et al. 2025).

System concepts have many fold applications in the bioeconomy e.g.:

- the production system of a bio-based resource (see e.g. ▶ Chaps. 5, 6, 7, 8, and 9)
- the value chain system of actors involved in producing, processing, marketing and consuming bio-based products (see ▶ Chap. 4)
- the innovation system for supporting change and transformation trough targeted ideas and activities.

Systems theory is a cross-disciplinary idea for the study of the abstract organization of phenomena, regardless of their substance, type, or spatial and temporal scale of existence. It investigates both the principles common to all complex entities and the (usually mathematical) models that can be used to describe them (Pohl et al. 2021).

The core components of a system are: (i) elements that are connected by (ii) relationships and separated by (iii) boundaries from its (iv) environment; systems are not bound to a scale but they can be nested, so that systems may contain (v) subsystems or be part of an overarching system of systems (Schiere et al. 2004). Furthermore, a system is a mental model that can provide analytical guidance when tailored and configurated to a particular situation (Ison 2012).
For a comprehensive overview of the concept of systems thinking, see the first edition of the bioeconomy book (▶ Sect. 4.3 in Knierim et al. 2018).

Do you want to learn more about system thinking? Take a look at ◘ Supplementary Video 3.3, a video from our MOOC 'Concepts of Sustainable Bioeconomy' (2021), where systems theory is explained in more detail.

The systems we consider tend to be production systems or supply networks. In a bioeconomy system, the value creation can be represented in a simplified value chain, which can be seen as a micro-level system of analysis: from raw material production, through processing, to products (see ▶ Chap. 4). At first sight, the components of a bio-based value chain are generic to other production systems such as those based on fossil resources. However, in contrast to fossil fuels, biomass cannot be 'simply' harvested or conveyed. Biomass production is distributed globally, subject to different biophysical conditions (e.g. climate, soil, water availability) and results in a wide variety of biomass (e.g. plants species). Our current linear models ('take-make-waste') focus on investigating specific components or details by isolating the objects of investigation. However, by ignoring dynamic interactions and the non-linear, complex context, we rely mainly on linear thinking and single knowledge areas (e.g. techno-economic knowledge), even though we are confronted with complex systems (Onyeali et al. 2023).

Systems thinking has proven its usefulness as an approach that seeks to depart from linear thinking in order to model complexity. Initially, it extends the model of simple causation (cause-effect) by introducing feedback loops (reciprocity), and linkages to other entities. Feedback loops and linkages between several elements are necessary, but not sufficient to characterize a group of elements as a system. In systems, the elements interact in such a way that new collective patterns and regularities emerge, and larger entities have properties that the individual elements do not ('the system is more than the sum of its parts').

Bioeconomy systems are multi-level, shaping and being shaped by social and ecological systems at local (e.g. landscape transformation) and global (e.g. greenhouse gas emissions) scales (Wohlfahrt et al. 2019). Biomass comprises diverse components (e.g. lignocellulose, proteins, sugars, starches, oils), which are fractionated during processing for various uses (Kircher 2021). The spatial dispersion, temporal dependencies, and interplay between sectors and actors (farmers, industries, policymakers, researchers and consumers) add to the bioeconomy's complexity. These actors operate within and influence interconnected systems, from local communities to global markets. In addition to the material needs that a bioeconomy system aims to satisfy, other goals and functions include the replacing non-renewable resources with locally available biomass, closing material and energy loops (i.e. circularity) and increasing biomass use efficiency (i.e. cascading biomass use, biorefinery approach) (Diaz-Chavez et al. 2020; Kardung et al. 2021; Wohlfahrt et al. 2019).

As explained in ▶ Sect. 3.3, the conditions governing the circularity of biomass flows are different from those of metal and mineral flows. Biodegradability imposes limits on the storage and reuse of bio-based materials, and the disposal or landfilling of biodegradable waste poses different environmental and societal problems than the landfilling of minerals and metals. The trade and deployment of biomass is also based on other functional contents: for example, nutritional value, energy value, structural strength, water content, and unquantifiable properties such as taste, smell, and appearance. The interaction of these conditions has led to a wealth of circular bioeconomy practices, including nutrient recovery from wastewater treatment, paper recycling, and energy provision from biogas and sawmill residues. These practices integrate multiple systems (i.e. couple different sectors), including water and sanitation, food provision, and wood-based construction sectors. Consequently, system integration, also referred to as multisector coupling, is a fundamental component of the bioeconomy (Schipfer et al. 2024).

System complexity arises from the attributes of its elements, their interrelationships, and the system's interactions with its context. Bioeconomy systems, embedded in local ecosystems and the broader natural environment and social context, require a systems perspective to understand their elements, relationships and outcomes (Vargas-Hernandez et al. 2018; Schlaile et al. 2025; Vargas-Carpintero 2025).

Due to the disciplinary diversity of systems theories, there are many ways to differentiate the systems concept. ▶ Chapter 37 presents a number of attributes that are commonly applied to differentiate between systems that are useful in the context of inter- and transdisciplinary research, namely openness, goals and functions, and system assessment.

When identifying and studying solutions in the bioeconomy system, we need to recognize all the different parts of these complex systems. A systems approach is necessary to understand the respective context, see multiple perspectives and allow different solutions to emerge. ◘ Table 3.1 shows some exemplary factors and characteristics of a bioeconomy system.

A holistic systems approach aims to understand and optimize the complex relationships and feedback loops between various actors and elements, such as natural resources, production processes, consumption patterns, waste management, and socio-economic factors in the regional context (◘ Fig. 3.8).

A holistic understanding of these relationships can help identify strategies to promote

change towards more resilient systems. Systems thinking thus has immense potential to enhance our understanding of complex situations, recognize interdependencies and relationships, and to relate our own perceptions and judgements to those of others in an engaged way. For this to happen, it is necessary to consider how novel innovations in the bioeconomy can be assembled, rather than focusing on individual elements, reflecting on the current system status and its drivers (Darnhofer 2021).

> ***Holistic systems thinking*** in the bioeconomy refers to an integrative approach that considers the entire system of biological, economic and social interactions.

Applying a holistic systems perspective to the analysis of bioeconomy systems also implies taking a multi-level approach that considers relationships at different levels, from micro (i.e. farming system, value chain), meso (i.e. landscape, region, value web) to macro (i.e. national and global level). Current approaches and projects tend to be based on a limited view of a bioeconomy, for example, focus on individual bio-based value chains, and thus fail to provide an integrated approach to the bioeconomy system under review. This narrow perspective can lead to oversimplification, which can generate controversies that discredit the potential or neglect potential risks of interventions aimed at promoting the bioeconomy.

Rather than focusing on individual components (e.g. biomass production), a systems thinking perspective examines the interconnectedness and interdependencies within the bio-based value chain. Holistic system thinking means that a sustainable bioeconomy system considers not only the basic components and the technological perspective (biomass production, processing, products and end-use), but also local socio-economic and ecological factors and the overall context (Vargas-Carpintero 2025; Schlecht et al. 2024) (see ▶ Chap. 4). For example, rather than seeing agricultural systems purely as biomass suppliers in a value chain, the analysis and design of the sub-systems of bio-based value chains requires the consideration of the relationships within them (at farm, landscape and

Table 3.1 Exemplary factors and characteristics influencing a bioeconomy system

Time scale dependencies	The timescales of biomass feedstock production and natural cycles can be very different, leading to a diversity of production cycles: for example, annual or perennial crops in agriculture; 10–100 years in forestry systems.
Spatial distribution	Fossil resources are unevenly distributed globally. In contrast, biological resources are found all over the world. Biomass production is globally dispersed due to the interaction of regionally specific biophysical factors that influence productivity (e.g. soil, climate).
Geographical conditions	The bioeconomy is based on varying geographical conditions. This regionality can be seen, for example, in biomass production. It depends on agricultural practices, workforce, biophysical conditions such as soil-related factors (water and nutrient availability) and climate, which differ from region to region. Territorial-scale logistical issues such as the location of water supplies or roads also have an impact.
Diversity and variability	Alternative resources and process flexibility are important characteristics of bioeconomy systems. The same feedstock can be used for multiple products (biorefinery approach), providing multiple functions.
Interactions	Connection and relations between different elements of biophysical, technological, socio-economic and institutional systems as well as between sectors and actors (e.g. farmers, foresters, energy producers, policymakers, scientists and local communities) influence the Bioeconomy system.

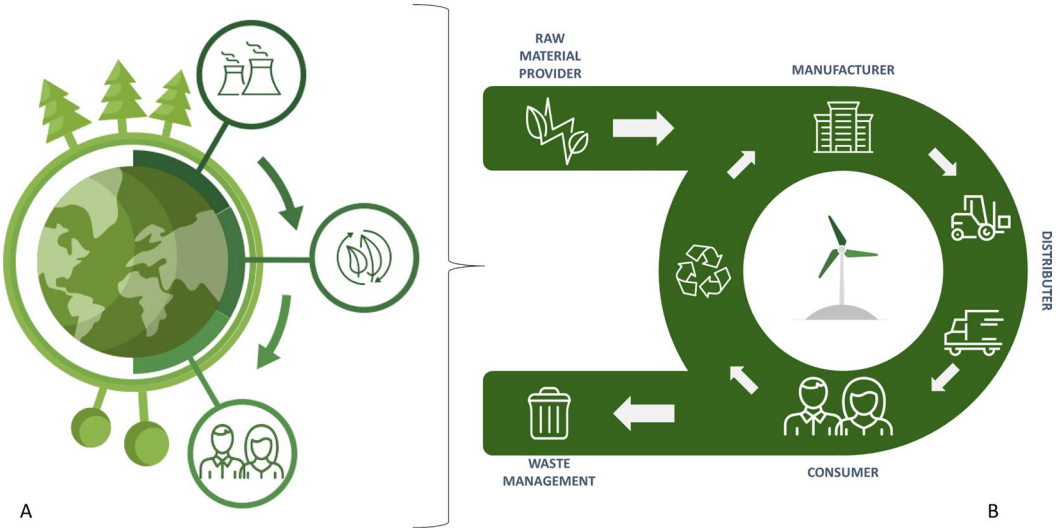


Fig. 3.8 Bioeconomy systems are embedded in a larger (regionally specific) context: **a** on a global scale via dispersed biomass production systems, and **b** at the local level through value chain components and actors

regional levels) and their context (off-farm activities, natural environment, biomass use, processing and consumption) (Darnhofer 2021).

Practical implications:

- Use systems thinking to empower change and foster transformation processes
- Understand the system, its components the actors involved within and outside the production system
  - Biomass production
  - Biomass processing
  - Bio-based products
  - Contextual factors, elements and actors
- Identify and define common ground: goals and objectives integrating different perspectives
- Identify multiple possibilities and strategies simultaneously
- Evaluate options to identify (regionally) specific solutions
  - Use a comprehensive set of indicators (number and quality), aimed at meeting sustainability and circularity requirements in the local context
  - A bioeconomy system analysis should be based on the biological, ecological, social, economic, institutional and technological systems
  - Use tools like life-cycle thinking in the analysis and design of bioeconomy systems (see ▶ Sect. 41.1).

Questions

1. What role does systems thinking play in the bioeconomy, and why is it necessary to move beyond linear models?
2. What are the potential environmental trade-offs of transitioning to a bioeconomy?
3. How does the bioeconomy align with resilience principles, and in what ways can it contribute to both climate mitigation and adaptation?
4. What is the primary goal of circularity within the circular economy, and how is this concept aligned with the objectives of a bioeconomy?
5. How do biorefineries contribute to the goals of a circular bioeconomy, and what are their main benefits for sustainable resource management?
6. Why is the integration of multiple scientific disciplines and types of knowledge critical for the development of a sustainable bioeconomy?

Answers

1. Systems thinking is crucial in the bioeconomy because it enables us to

understand and model the complexity of interrelated processes and actors in ecological, social and technological contexts. Unlike linear models, which focus on isolated cause-and-effect relationships, systems thinking incorporates feedback loops, linkages and emergent properties, helping to reveal how interactions between components produce collective patterns that individual elements alone do not exhibit. This approach is essential for understanding and managing the multi-level impacts of the bioeconomy, such as landscape transformation and greenhouse gas emissions, which operate at both local and global scales.

2. The transition to a bio-based economy can reduce reliance on fossil fuels, but it also poses environmental trade-offs, such as increased land and water use for biomass production, potential habitat loss, and impacts on biodiversity. Additionally, large-scale agriculture for bio-based materials can lead to soil degradation, water pollution, and greenhouse gas emissions if not managed sustainably. Balancing these factors is crucial to ensure that the environmental benefits outweigh the potential downsides.
3. The bioeconomy is in line with the principles of resilience through the promotion of systems that are regenerative, diverse, and adaptable to shocks—key characteristics of resilience. It contributes to climate change mitigation through carbon sequestration, clean energy production, and the creation of carbon sinks, such as afforestation. With respect to climate change adaptation, the bioeconomy promotes climate-resilient agricultural practices, such as conservation agriculture, agroforestry and organic farming, which help ecosystems and communities withstand climate change. By integrating these strategies, the bioeconomy supports both environmental stability and sustainable development in the face of socio-economic and climatic shifts.
4. The main goal of circularity in a circular economy is to minimize resource input and waste generation by slowing down, closing and narrowing material and energy loops through pro-cesses such as recycling, reuse and eco-design. This approach is regenerative and aims to reduce environmental impacts and preserve the value of materials. Circularity is well aligned with the bioeconomy through its promotion of efficient biomass use and conversion of waste into new resources, thus maximizing the sustainability of biological materials. This synergy between circularity and the bioeconomy, referred to as the 'circular bioeconomy', emphasizes the more effective use of natural resources and the creation of value from waste, contributing to the sustainable transition of eco-nomic systems.
5. Biorefineries are essential for a circular bioeconomy, as they convert biomass (including agricultural residues and waste streams) into valuable bioproducts such as biofuels, biochemicals, and bioenergy. Using integrated technologies, biorefineries maximize the use of biomass and minimize waste, thus supporting sustainable resource management. In the circular bioeconomy, biorefineries help close loops by transforming waste into resources, such as bio-based fertilizers that sup-port agriculture. By utilizing local biomass, biorefineries reduce reliance on fossil fuels and foster regional resource security, creating economic, environmental and social benefits that are critical to sustainability goals.
6. The sustainable development of a bioeconomy requires the integration of multiple scientific disciplines because it addresses complex 'wicked problems' that involve interdependent social, ecological and economic factors. For example, agricultural science contributes knowledge on sustainable farming practices, while economics provides insights into market dynamics and resource allocation. The integration of scientific, tra-

ditional, normative and transformative knowledge from diverse fields enables a more comprehensive understanding of the challenges of the bioeconomy, contributing to the development of sustainable solutions and facilitating effective cooperation among a variety of actors.

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Bio-Based Value Chains and Webs

Ricardo Vargas-Carpintero and Valentin Schlecht



Fig. 4.0 Bio-based value chains and webs. (© Ricardo Vargas-Carpintero) (▶ https://doi.org/10.1007/000-hte)

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The transition to a sustainable bioeconomy entails the transformation of production towards the creation of environmental, social and economic value. Production activities in economic sectors are framed in value chains, in which value is generated through a sequence of processes for delivering goods to consumers. In the context of the bioeconomy, production systems utilise biomass as the main renewable raw material, convert it through a variety of technological options and deliver bio-based products and services. Through these value-adding activities, economic value is generated. Aiming to shape multi-functional production systems, bio-based value chains and webs should have a positive impact on the environment and society. In this chapter, the concepts of bio-based value chain and web are introduced as integrative frameworks to link biomass supply, processing, products and markets. By means of examples of emerging bio-based value chains and webs, key characteristics of these systems will be explained. This chapter emphasises that bio-based value chains and webs require both technical and organisational as well as governance dimensions for their sustainable development and performance.

Learning Objectives

After studying this chapter, you will…

- …be able to describe the bio-based value chain and web concepts and identify their main components from primary production of biomass to final products (see ► Sects. 4.1, 4.2 and 4.3).
- …be able to describe common characteristics of bio-based value chains and webs as part of bioeconomy systems (see ► Sect. 4.4).
- …be able to apply the bio-based value chain and web as operational frameworks to enable multi-actor collaboration, inter and transdisciplinarity and systems thinking in the bioeconomy (see ► Sect. 4.5).

4.1 The Bio-Based Value Chain as an Integrative Framework: An Introduction

Bio-based value chains and webs can be seen as the operative side of the bioeconomy, the cell of a larger organism called 'bioeconomy system'. This 'cell' is complex and builds on biological resources, processes and interrelated actors and stakeholders to produce bio-based products and services. As in the case of muscle or brain cells, value chains and webs need to be adapted to specific contexts and for the delivery of specific needs, with the imperative to contribute to social wellbeing and environmental regeneration.

4.1.1 Relevance and Utility of the Concept

Bioeconomy strategies worldwide and their action plans seek to promote new economic activities based on the use of renewable resources to pursue sustainability goals at regional, national, and supranational levels (see ► Chap. 2). Unlocking the potential of the bioeconomy, from a bioresource vision perspective (see ► Sect. 2.3) requires setting up production systems (i.e. value chains) able to create value by producing, supplying and transforming biomass into final products and services (Bugge et al. 2016; Viaggi 2018).

According to Ronzon et al. (2022), value chains of the European bioeconomy generate 657 billion euros of value added, from which 29% is represented by agriculture and 36% by food, beverages and other agro-manufacturing products. These value chains contribute 4.7% of the EU GDP and employ 8.3% of the labour force, making it a key socio-economic sector. This shows that bio-based value chains are already established to produce food, energy, chemicals, pharma and bio-based materials, and new ones are being developed globally (Kircher 2021). Bioeconomy strategies at supranational, national and regional levels aim to generate economic value, create

jobs and improve environmental performance. Here, the deployment of sustainable bio-based value chains and webs plays a key role.

In bioeconomy, value chains are built on biological resources and therefore called 'bio-based'. The term is commonly used to illustrate and describe economic activities (i.e. adding value) within the bioeconomy. They are essential to the operationalisation and implementation of the bioeconomy, as they integrate the inherently interconnected processes of natural resource use and management related to the production of biomass, but also its processing and utilisation.

The bio-based value chain provides an operational framework that represents, fosters and enables (Zörb et al. 2018; Viaggi 2018; Kircher 2021):

- The connection between primary production of biomass, processing, bio-based products and services, and markets
- The economic activity performed by manifold coordinated actors and organisations for the production and use of biomass
- The uptake and articulation of innovation stemming from scientific research and ranging from bioprospecting to novel products, sustainable management, and new business models
- Systems thinking and life-cycle thinking for value chain design, development, analysis and impact improvement (see ▶ Chap. 3).
- A micro-level bioeconomy system analysis for improving value creation, logistics, cost structure, actor relations, and sustainable performance.
- A meso- and macro-level bioeconomy system analysis to understand the relations between single value chains at sectorial, regional, national, and global levels.

4.1.2 Concept of Bio-Based Value Chain

Production activities in economic sectors are based on interdependent relationships between economic agents. The linkages among actors, the flow of materials and goods from the extraction of raw materials to the distribution and marketing of final products, as well as the flows of information and trade interactions result in complex systems. These systems are known as value chains, in which actors are connected and create value along a set of production processes that result in a final product and/or service. In the context of the bioeconomy, these production systems are known as 'bio-based value chains'. Let's explore what this means.

> The term ***value chain*** describes the full range of activities which are required to bring a product or service from conception, through the different phases of production (involving a combination of physical transformation and the input of various producer services), delivery to final consumers and final disposal after use. A value chain is based on actors (e.g. firms), their relationships, and coordination mechanisms (Kaplinsky and Morris 2002; Gereffi et al. 2005).

Bio-based value chains consist of actors that perform adding value processes and economic activities using biomass as resource base. In these production systems, farmers, processors, and distributors interact and directly add value in a coordinated form (Gereffi et al. 2005). Indirect actors such as input and service providers, researchers and regulatory bodies support the system and provide an enabling environment among them (Gereffi et al. 2005). In addition to direct and indirect value chain actors, key stakeholders in bio-based value chains include workers, local community, consumers and society (Marting Vidaurre et al. 2020). The bio-based value chain is described as the 'sequence of processes from biomass production to bioproduct along with its opportunities for value generation, including economic, social and ecological values' (Lewandowski 2015). The simplified structure of the bio-based value chain consists of three main components or building blocks: biomass production, biomass processing, and bio-based products (Zörb et al. 2018), supported by ecosystem services and value chain actors, as illustrated in Fig. 4.1.

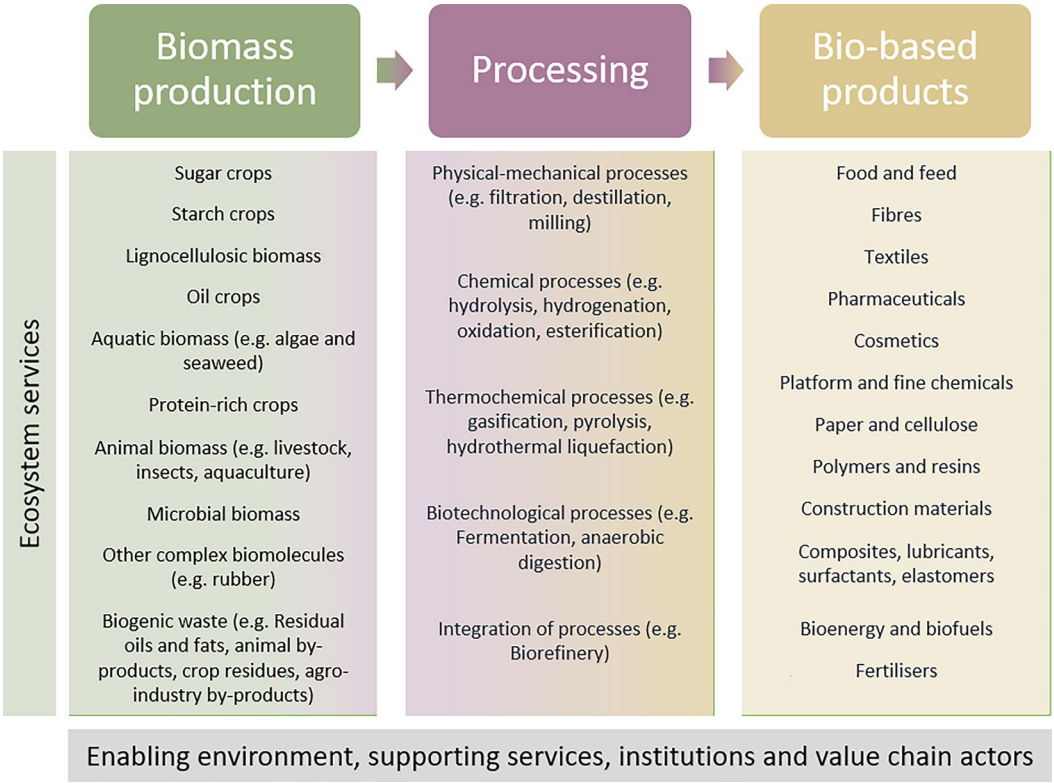


Fig. 4.1 Simplified structure of a bio-based value chain with its main components (Adapted from Iffland et al. 2015 and Abdulsamad et al. 2013)

Bio-based value chains are based on the combination of natural resources (e.g. biological organisms, soil, light, water, ecosystem services, minerals, etc.), technological inputs (e.g. crops, cropping systems, harvesting and post-harvesting techniques, processing technologies, biorefining, transport, etc.), direct and undirect value chain actors (organised and coordinated through value-chain governance structures) and supporting services (i.e. knowledge, regulations, funding, certifications, etc.).

A ***bio-based value chain*** is a linked sequence of value-adding processes performed by coordinated actors from biomass production to final bio-based product or service, including disposal/recycling, for the generation of environmental, social and economic value (Kaplinsky and Morris 2002; Gereffi et al. 2005; Lewandowski 2015).

The concept of the bio-based value chain is relevant as it describes the supply side of the bioeconomy and value-adding processes (Viaggi 2018). It provides a general and multidimensional framework focused on the creation of value, involving input and product flows, actors, governance arrangements as well as different processes, from logistics to sustainability management. In bio-based value chains there are flows of materials (e.g. biomass) from primary production to end products, with possible returns due to recycling and circularity. Information flows are also a feature of bio-based value chains, primarily regarding sustainability performance, but also market information such as price, offer, demand and monetary flows. Figure 4.2 depicts a more detailed view of the bio-based value chain.

Complementary concepts, such as supply chain, process chain and global chain are useful to zoom in and out in the bio-based value chain. For instance, biomass or bio-based

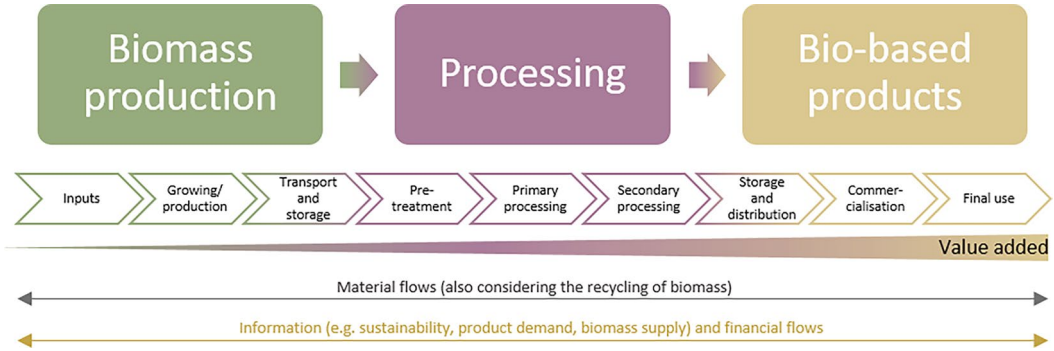


Fig. 4.2 Detailed view of a bio-based value chain indicating processes, value addition and flows. (Adapted Iffland et al. 2015; Abdulsamad et al. 2013; Zörb et al. 2018)

product supply chains (e.g. wood supply chain, biogas supply chain) focus on the logistics and operational perspective of material and information flows (Clay and Feeney 2019). Process chains describe the processes, activities, and operations required in the complete value chain or at a specific segment of it (e.g. pre-treatment, biorefining and downstream processes as part of the biomass processing segment), as shown in Fig. 4.2 (Zörb et al. 2018). Global commodity chains and networks (e.g. palm oil chain) help to explain the organisation of global bio-based industries (Gereffi et al. 2005).

4.2 The Origins of the Bio-Based Value Chain Concept

But is the bio-based value chain a new concept? The term value chain has its roots in the concept of *filière,* a French term originated from economics and introduced in the 1970s as an analytical framework for the vertical structuring of production systems and coordination between actors to produce goods (Biénabe et al. 2017).

In essence, this concept refers to the linked sequence of technical, logistical and commercial operations in agricultural production systems for the production and distribution of products such as food, from production to consumption (Lançon et al. 2017). The *filière* allows a sub-division of production systems and the interdisciplinary analysis of input-output relationships (technical perspective) as well as organisation of economic agents and the forms of exchanges (social and economic perspectives) (Biénabe et al. 2017; Lançon et al. 2017). This framework has been primarily used in the context of agricultural production systems and rural development as a diagnostic tool to analyse the performance, organisation and relations between farmers and processors and improve the competitiveness of agricultural value chains (Biénabe et al. 2017; Zörb et al. 2018 cited Nang'ole et al. 2011).

In fact, agricultural value chains and similar concepts such as agri-business and agro-industrial value chains are closely related to bio-based value chains because of the resource base they are built on: biomass. However, in the case of bio-based value chains, other forms and sources of biomass are considered, encompassing both traditional and new biomass types. These include biomass from conventional agriculture (i.e. crops and livestock production) but also aquaculture, forestry, microorganisms, algae cultivation, insect farming and residual biomass generated at primary production, industry or consumer level.

> A ***filière*** is a linked sequence of technical, logistical, and commercial operations necessary to produce and distribute food or agro-industrial products, from production to consumption (Lançon et al. 2017).

An extension in the scope of the *filière,* given the need to understand global value chains, led to the introduction of the 'global commodity chain' concept in the mid-1990s to analyse the coordination of large value chains (Kaplinsky und Morris 2002). These systems are characterised by globally distributed and linked actors and processes for adding value from the raw material extraction to the final product (Gereffi et al. 2005; Kaplinsky and Morris 2002; Viaggi 2018). The characteristics of these production systems can also be identified in large bio-based value chains with a global distribution of activities, as is the case in the food system. Thus, the 'global commodity chain' or 'global value chain' concepts set a baseline to understand the structure, operation and coordination of more complex bio-based value chains that operate with or to produce bio-based resources and products at a global scale.

In the 1980s, Michael Porter introduced the value chain concept as an enterprise-level and management tool for analysing a firm's competitive advantage, based on the primary and support activities within the firm that result in value creation (Zörb et al. 2018 cited Porter 1985). It can be understood as a zoom-in on every firm's operation that is part of a larger value chain, in which multiple firms and various actors interact, from raw material production to final product. It can be the case, however, that if a firm's strategy is based on a complete vertical integration, the same firm fulfils all value chain processes.

4.3 The Bio-Based Value Web: Beyond Linear Thinking

The simplicity of the value chain and its linear representation contrasts with the complex reality of production systems. Multiple inputs, biomass and supporting service providers, as well as a variety of intermediate and final products and distribution channels, result in interlinked value chains, creating value webs or networks (Kaplinsky and Morris 2002; Zörb et al. 2018). An example is the elaboration of a final product that requires different components and depends on various bio-based value chains, such as a car that operates on renewable energy and is built with bio-based materials (Fig. 4.3).

The concept of biomass-based value web (or bio-based value web) was introduced by Virchow et al. (2016) as a systems approach to account for the linkages between single value chains, capture the variety of biomass pathways and explore synergies for sustainability and productivity.

Bio-based value webs integrate multiple bio-based value chains into a cohesive network, expanding beyond the focus of a single product or value chain (Virchow et al. 2016). These webs enable the incorporation of diverse biomass-to-product pathways, linking various stakeholders and fostering collaboration across different sectors (Virchow et al. 2016; Vargas-Carpintero et al. 2022; Zörb et al. 2018). This approach provides a holistic view of complex production systems and processes. It facilitates a 'web perspective' to understand the multiple uses of biomass, the connections between value chains, how these are governed and how actors are linked (Virchow et al. 2016; Viaggi 2018). Multiple products from a single biomass type (e.g. multi-purpose crops that can serve multiple functions and flex crops with interchangeable uses for food, feed, energy and materials), multi-feedstock systems and the product mix at farm level can be analysed from a value web perspective (Virchow et al. 2016; Viaggi 2018; Bastos Lima 2018; Birner 2018; Scheiterle et al. 2018). An example of the manifold uses of sugar cane in a value web is illustrated in Fig. 4.4. The value web approach is helpful in identifying synergies between value chains, innovation opportunities, increasing resource efficiency through the cascading use of biomass and circularity principles, assessing the system's sustainability and value creation, developing production scenarios, and formulating upgrading strategies (Zörb et al. 2018).

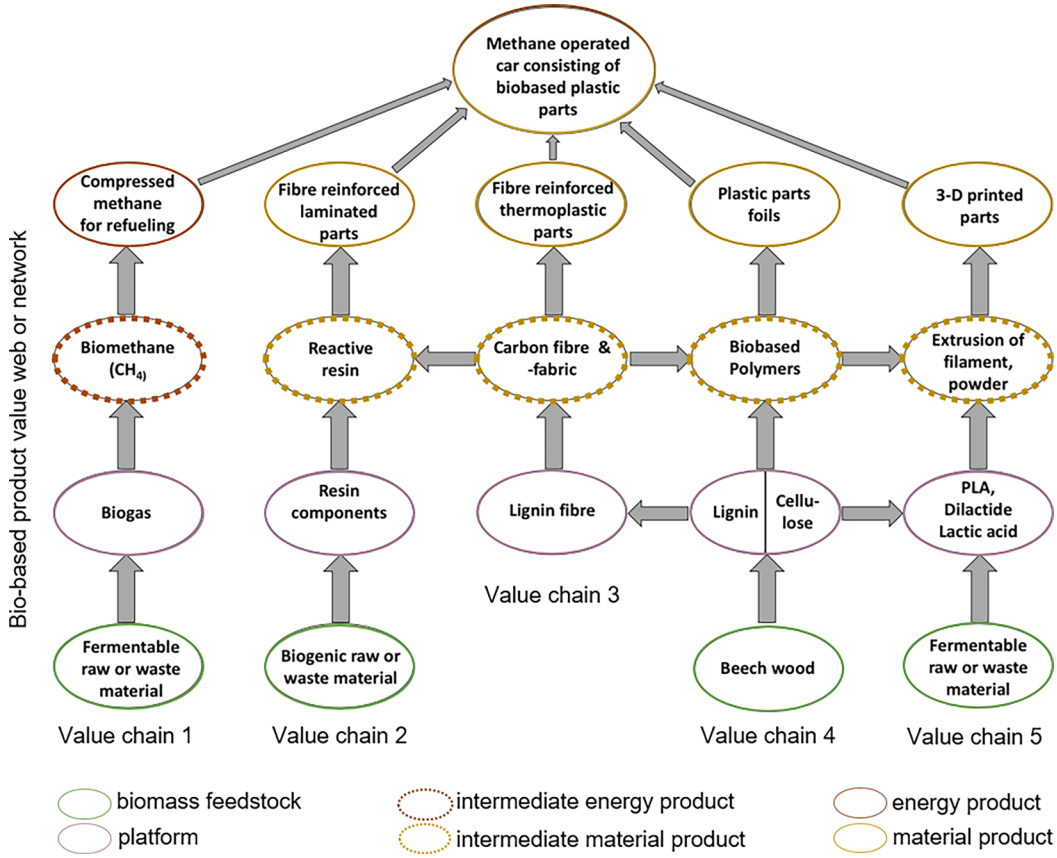


Fig. 4.3 Value web or network of a car operated with bio-methane and built with bio-based plastic parts. Multiple value chains are integrated, consisting of feedstock (biomass), platforms or building blocks, intermediate products and final material and energetic products. (Adapted from BIOPRO in Zörb et al. 2018)

A ***biomass-based value web*** represents an extension of the value chain concept used to analyse the manifold uses of biomass in the bioeconomy. A biomass-based value web approach utilises the 'web perspective' as a multi-dimensional framework to understand the interrelation and linkages between several value chains and how they are governed (Virchow et al. 2016; Scheiterle et al. 2018; Birner 2018).

Do you want to learn more about the concepts of bio-based value chains and webs? Take a look at Supplementary Video 4.1, a video from our MOOC "Concepts of Sustainable Bioeconomy" (2021).

4.4 Characteristics of Bio-Based Value Chains and Webs

Bio-based value chains and webs are at the heart of the bioeconomy, offering a sustainable alternative to traditional, fossil-based systems. These systems are unique in their reliance on renewable biological resources, their integration of diverse stakeholders, and their focus on environmental, economic and social sustainability. The following section explores their defining characteristics, highlighting their role in fostering innovation and resilience within a sustainable bioeconomy.

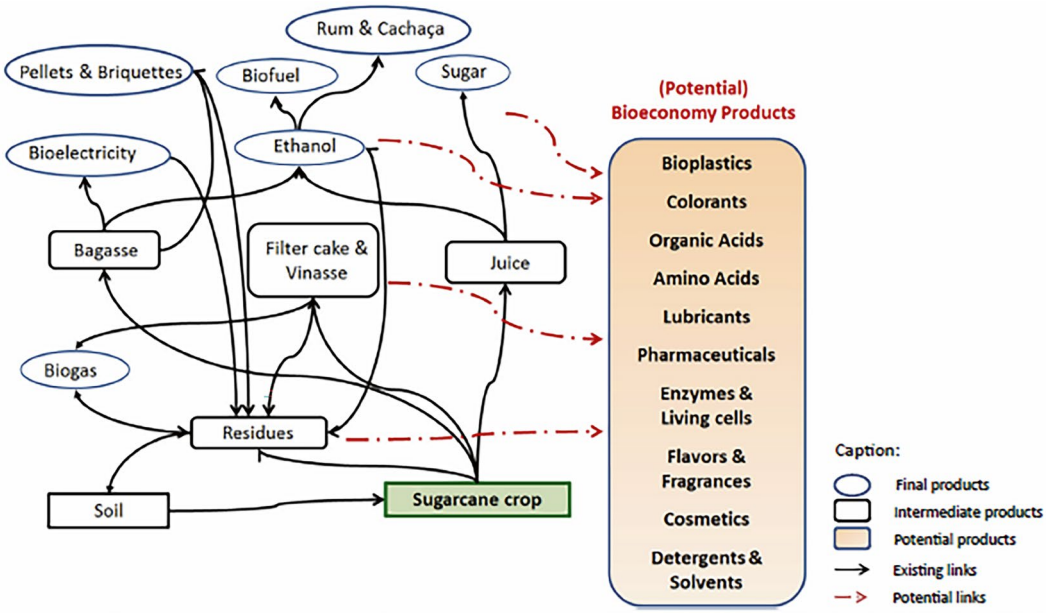


Fig. 4.4 Sugar cane value web in Brazil showing the manifold uses of a single crop (Scheiterle et al. 2018 in Birner 2018)

4.4.1 Biomass Dependency

The availability of biomass is essential for the implementation of bio-based value chains and webs. Ensuring a sustainable production of biomass is crucial, without negatively impacting food supply, ecosystem functioning and natural resources, such as land and water. Strategies to achieve this include improving biomass production efficiency through sustainable intensification, using waste materials, and developing systems that require smaller amounts of biomass (Lewandowski 2017; MacClay and Sellare 2022). New sources of biomass such as second-generation feedstocks (e.g. residual biomass, non-edible crops and lignocellulosic plants), third-generation feedstocks (e.g. microalgae) and fourth-generation inputs (e.g. genetically modified microorganisms), can contribute to the production of bio-based energy and material products without competing with food production. These biomass sources aim to reduce direct and indirect land use change by, for example, cultivating multipurpose crops on marginal lands while contributing to land restoration and carbon sequestration. Residual biomass from bio-based industries is another important resource, which can create new business models and link bio-based and non-bio-based sectors (Carraresi et al. 2018; MacClay and Sellare 2022). Novel multi-purpose crops that can serve different applications for food and non-food uses are pivotal for the diversification of bio-based resources and products (Virchow et al. 2016) (see example in ▶Excursus 4.1).

Do you want to learn more about emerging bio-based value chains and webs for producing bioplastics, chemicals, bioenergy/biogas and providing ecosystem services from the lignocellulosic crop miscanthus? Take a look at Supplementary Video 4.2, a video from our MOOC "Concepts of Sustainable Bioeconomy" (2021).

4.4.2 Biomass Complexity

Unlike fossil-based resources like oil, biomass is a biological carbon source heterogeneous in its composition, with limited shelf life, spatially dispersed, seasonal and with low energy

Excursus 4.1: Macaúba Palm for Emerging Bio-Based Value Webs

The macaúba palm (*Acrocomia aculeata*), native to Latin America, is an alternative oil crop for the food and feed, cosmetic, chemical and bioenergy sectors by the full use of the fruits (Fig. 4.5). Value chains and webs from this plant are being established driven by the domestication of the palm and its initial cultivation in Brazil (Vargas-Carpintero et al. 2021, 2022).

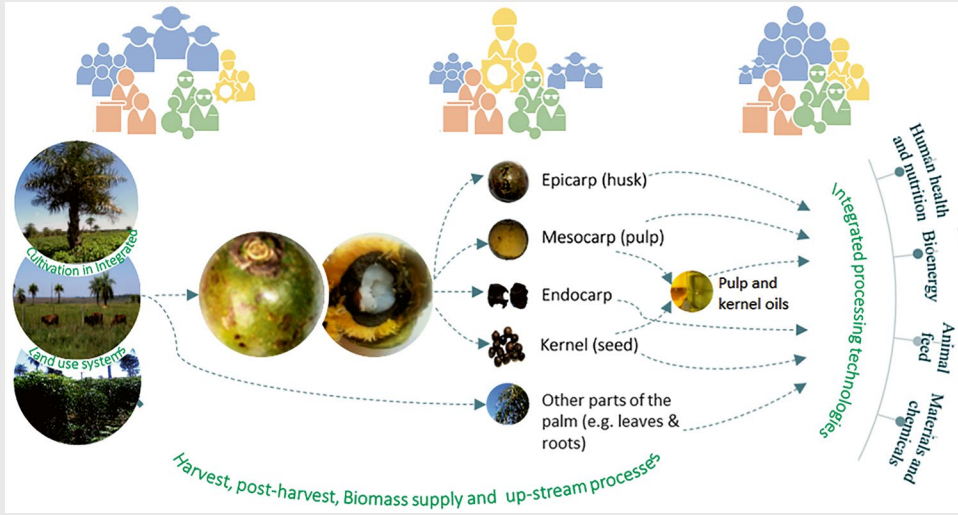


Fig. 4.5 Acrocomia value web concept depicting integrated land use systems for the cultivation the macaúba palm (*Acrocomia aculeata*) and other palms of the genus *Acrocomia*, the integral use of fruits as main plant product and the range of bioeconomy sectors for macaúba-based products and oils, along with key actors that shape the value chains, such as farmers, processors, researchers, institutions and consumers. (Adapted from Vargas-Carpintero et al. 2022 licensed under CC BY 4.0. ► https://creativecommons.org/licenses/by/4.0/)

and carbon density (Kircher 2021; Aristizábal-Marulanda and Cardona 2019; Cardona et al. 2019). Biomass can be very diverse in its composition, forms, and properties. In addition, biomass production requires inputs such as seeds and fertilisers, and natural resources, different than oil that is available for its extraction (Kircher 2021). These characteristics of raw materials make bio-based value chains distinct in their configuration and operation. For example, decentralised biorefineries with smaller processing capacity than conventional oil refineries are closely located to biomass production areas (Kircher 2021). Flexibility strategies can also be considered in integrated biorefineries that use flexible processing pathways for the conversion of multiple biomass types into manifold products, as a measure to overcome biomass seasonality, reduce risks and diversify the market (Espinoza Perez et al. 2017; Zörb et al. 2018) (see ► Chap. 17).

4.4.3 Multiple Biomass Uses

Biomass derived from living organisms has different applications such as source of food, feed, energy, construction materials, fibres, cosmetics, pharmaceuticals and other bio-based products. Value chains encompassing these uses and sectors are part of what we call today bio-based value chains and webs. Although in the emergence of the bioeconomy concept bio-based value chains were rather dedicated to energy production, today multiple sectors and biomass uses are consid-

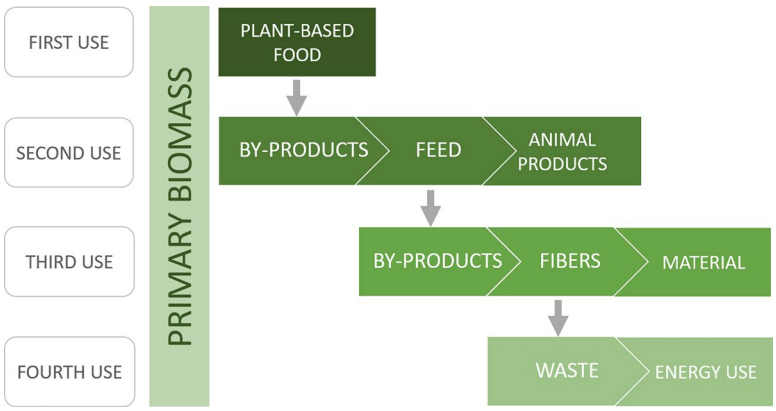
ered within the bioeconomy (see also ▶ Sect. 3.2). Deciding on biomass uses, such as food, energy or material uses, is a fundamental step that requires to prioritise the value of the product (economic but also socially and environmentally). The possibility of simultaneously deliver different products can be achieved using multi-purpose biomass sources, integrated processing technologies and through linkages between different value chains.

4.4.4 Integrated Processing and Multi-product System

Using the biomass as efficiently as possible is one of the main operating principles of bio-based value chains and webs. The cascading use of biomass, introduced in ▶ Chap. 3, is a concept to represent the extension of the life-cycle of resources (e.g. paper recycling) as well as a strategy to make full use of biomass components and by-products (◘ Fig. 4.6) (Zörb et al. 2018). For instance, in biorefineries (see ▶ Chap. 17) biomass can be fully processed through its fractionation into functional components through the combination of mechanical, biological, chemical and thermo-chemical processes for the conversion of biomass into a large set of intermediate and final bio-based products (Zörb et al. 2018; Kircher 2021). The concept of cascading use of biomass is complemented by circularity for closing material and energy flows (see ▶ Chaps. 3 and 17), by, for example, recycling nutrients that can be used in agriculture, valorising by-products, recovering energy, and capturing carbon (Zörb et al. 2018; Kircher 2021).

4.4.5 Multi-sectoriality and Involvement of Multiple Stakeholders

In bio-based value chains and webs, multiple economic sectors are involved. Both established and new biomass producing sectors including agriculture, forestry, fisheries, marine sources, the biotechnology industry and even waste management sectors provide bio-based resources to a range of established and novel bio-based sectors encompassing food and feed, energy and bio-based industries (chemical, pharma, cosmetics, textiles and biomaterials) (Kircher 2021; Viaggi 2018). Bio-based value webs from a single crop, such as sugar cane, can deliver several products for different sectors (◘ Fig. 4.4). The valorisation of residual biomass can also lead to new synergies between companies from different sectors (Carraresi et al. 2018) (see example in ▶Excursus 4.2). The connection between established and novel bio-based sectors is key for the integration of emerging bio-based value chains and webs (Zörb et al.



◘ **Fig. 4.6** Cascading use of biomass (Zörb et al. 2018)

Excursus 4.2: Interlinking Bio-Based Value Chains and Non-traditional Bio-Based Value Chains

The valorisation of residual biomass can result in novel value chains and the creation of bio-based value webs that interlink different sectors of the economy. One example shown in Fig. 4.7 looks at the use of residual press cake from vegetable oil extraction for phosphate recovery and its use as input in a mineral fertiliser value chain. This is possible by using enzymes in a biotechnological process that also generates press cake low in phosphate to be used in mixed feed (Carraresi et al. 2018).

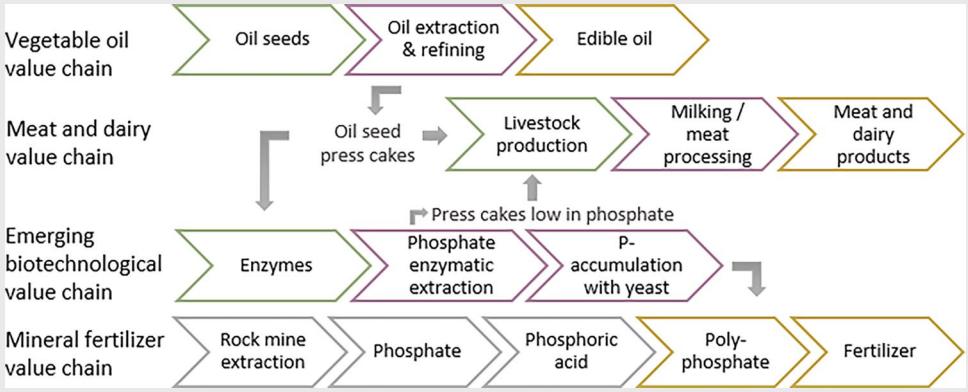


Fig. 4.7 Multi-sectoriality in emerging bio-based value chains and webs. An example is the phosphorus recovery from agricultural by-products such as oil press cakes from rapeseed to produce fertilizer and the use of press cake low in phosphate as animal feeding. (Adapted from Carraresi et al. 2018)

2018). Suppliers of biomass, farmers, transporters, handlers, primary and secondary processors, distributors and consumers are among value chain actors connected in these systems. But also policy makers, investors, scientists, certifying bodies, service and inputs providers (from upstream or downstream value chains, such as seed production), consulting and training services, and further stakeholders such as local communities and society interact.

4.4.6 Territoriality or Regionality

Bio-based value chains and webs are anchored to the place where biomass is produced. For instance, agricultural and forestry systems are spatially dispersed which affects transportation costs and indicates, among other reasons such as biomass composition and quality assurance, the need for decentralised value chain processes at regional level (Viaggi 2018; Kircher 2021). The approach of using available bio-based resources, adding value locally, operating in close proximity to the market, and contributing to rural economies, in addition to the geographical distribution of biomass, highlights the regional or territorial perspective of bio-based value chains and webs. Their presence in specific spaces forms in 'territorial bioeconomy systems' (Fig. 4.8), in which value chains are rooted in the local context regarding natural resources, stakeholders, material flows and operation, as in territorial or rural biorefineries (Wohlfahrt et al. 2019; Lucian Ceapraz et al. 2016). Regardless of the location of processes, a regional perspective is necessary along value-adding processes, from biomass production to product use, as processes interact with the local biophysical, economic and social context.

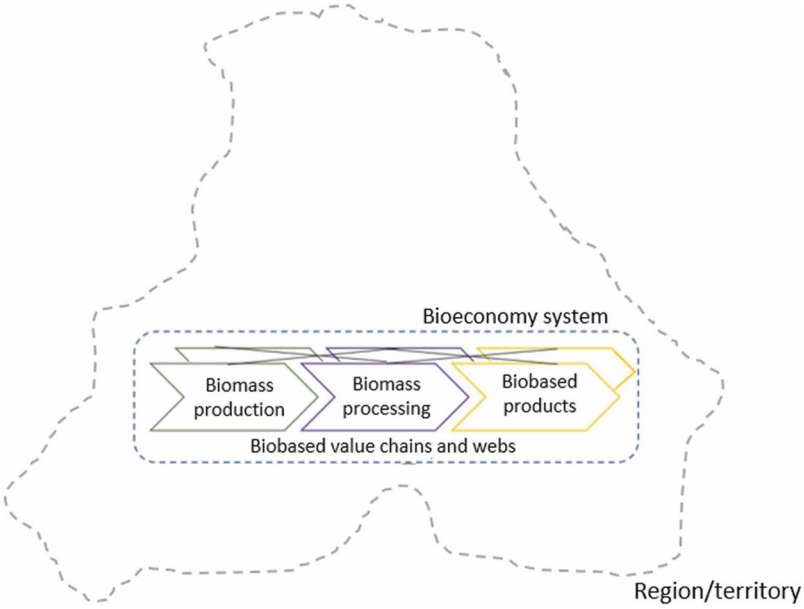


Fig. 4.8 Territorial embeddedness of bio-based value chains and webs. (Vargas-Carpintero 2025 licensed under CC BY 4.0. ► https://creativecommons.org/licenses/by/4.0/)

4.4.7 Context Dependency and Multi-dimensionality

Bio-based value chains and webs belong to bioeconomy systems, and as such, they are embedded in a biophysical, social, technical, economic and institutional context and operate within geographical boundaries (Fig. 4.9) (Wohlfahrt et al. 2019; Ge et al. 2016). Along bio-based value chains and webs' processes, value chain actors and other stakeholders utilise natural resources by employing technologies for biomass production, supply, transformation, and use (Wohlfahrt et al. 2019). Thus, interactions within and between biophysical or environmental, social and technical elements occur, particularly in agricultural systems and derived value chains (Lewandowski et al. 2024). For example, soil-plant relations determine biomass production, which can be influenced using fertilisers, whose application requires farmer's training. Thus, bio-based value chains and webs, from a social-ecological systems (SES) perspective, exert influence in their social and biophysical context, while also being shaped by them (Wohlfahrt et al. 2019; Ge et al. 2016; Viaggi 2018). The con-

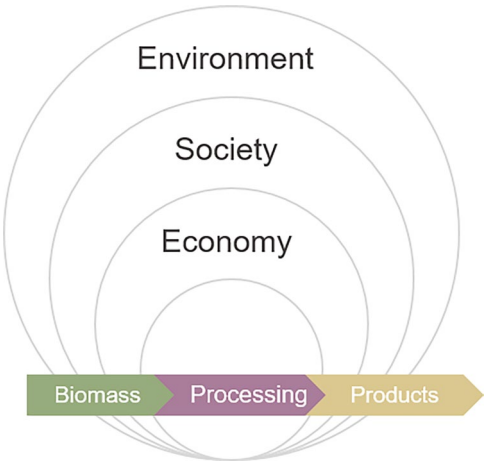


Fig. 4.9 Bio-based value chains and webs as embedded bio-based production systems in larger environmental, social and economic systems. (Adapted from Budzianowski and Postawa 2016)

cept of bio-based value web, because of its holistic principle, can be helpful to account for these interactions with the context. Further integration of multi-dimensionality in analytical frameworks adapted to the bioeconomy can help to understand system interactions, as proposed by Viaggi (2018) in the concept of 'socio-ecological-technological value web'.

4.4.8 Sustainability Orientation

In bio-based value chains and webs the aim is to have a positive performance in environmental, social, and economic terms (Lewandowski 2015). These systems are required to operate within planetary boundaries and their sustainability depends on the functioning of natural, technological, and governance processes (Ge et al. 2016; Wohlfahrt et al. 2019; Diaz-Chavez and van Dam 2020). The use of sustainably produced biogenic carbon from biomass aims to substitute and reduce the use of fossil carbon in the economy and in this way, mitigate climate change. In view of the degradation of ecosystems and their functions, bio-based value chains and webs, as the supply side of the bioeconomy, are required to be shaped in a way that the production of biomass and its use avoid land and food use competition, reduce greenhouse gas emissions, use fewer inputs, ensure the circulation of materials and energy, minimise waste, foster ecosystem services and restore degraded ecosystems (Lewandowski 2015; Lewandowski 2017; Viaggi 2018). In addition, social wellbeing, equality and inclusion are elemental goals (Palmeros Parada et al. 2020; Cerca et al. 2022; Marting-Vidaurre et al. 2020). Thus, along the design, development and operation of bio-based value chains and webs, the continuous consideration, evaluation and accomplishment of sustainability criteria from biomass production to final product, use, and disposal is essential to guarantee their positive performance and continuous improvement (Vargas-Carpintero 2025; Lago-Olveira et al. 2024).

4.4.9 Knowledge Base and Systemic Innovations

Research, development and innovation (RD&I) play a substantial role in the bioeconomy, commonly referred to as the 'knowledge-based bioeconomy' (Pyka 2017). The introduction of new crops, cropping systems, processing technologies, and products, as well as the adaptation of converging technologies such as digitalisation and artificial intelligence in bio-based value chain and web processes, requires RD&I. More sustainable biomass production practices (e.g. climate-resilient crop varieties, agroforestry systems, biological crop protection), more efficient and clean processing, as well as organisational innovations, constitute the knowledge base for the development and upgrading of bio-based value chains and webs. Bioeconomy innovations are systemic in the sense that these affect the whole value chain. Common challenges of bioeconomy innovations are related to commercialisation, diffusion, adoption, knowledge gaps between disciplines, acceptance and regulatory aspects, as well as high investment costs and long development timelines (Bröring et al. 2020). Addressing these challenges and reducing risks along the R&D development process requires of partnerships between actors of innovation systems (MacClay and Sellare 2022; Bröring et al. 2020; Van Lancker et al. 2016). In addition, the facilitation of value chain and web building processes through platforms that enable the connection between actors and collaborative environments can help to speed up the knowledge transfer and innovation adoption process (MacClay and Sellare 2022; Zörb et al. 2018; Vargas-Carpintero et al. 2022; Van Lancker et al. 2016).

Excursus 4.3: BiographieBW

The Federal State of Baden-Württemberg (Germany) is a pioneer case of regional bioeconomies. As part of the state's bioeconomy strategy, the formation of novel and advanced bio-based value chains and webs is a priority, based on research, development and innovation. The Fig. 4.10 displays an infographic where you can have an overview of the bioeconomy research program that has been implemented to advance the knowledge base of the state's bioeconomy.

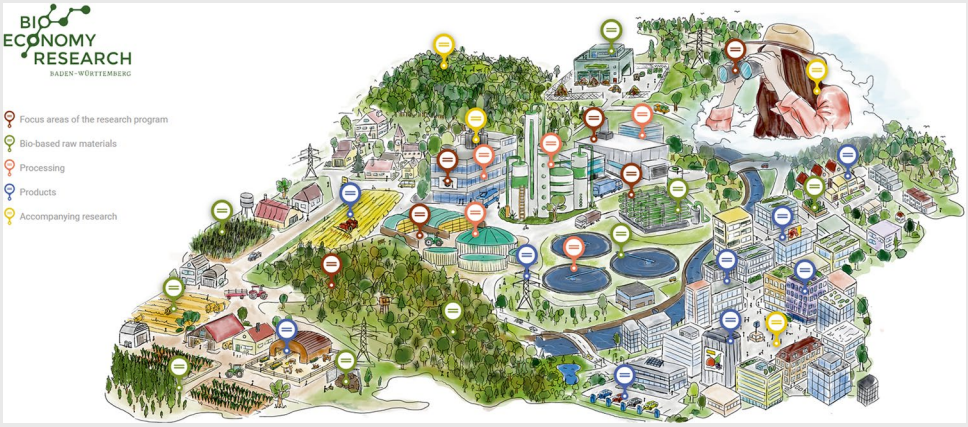


Fig. 4.10 Regional approach to R&D research in bioeconomy: the case of Baden-Württemberg ► https://biographiebw.uni-hohenheim.de/ © Universität Hohenheim

4.5 Design and Development of Bio-Based Value Chains and Webs

The design and development of bio-based value chains and webs is a complex process that requires a system perspective, integrating both technical and non-technical aspects (Fig. 4.11). Technical aspects refer to the design and optimisation of production systems through the integration of processes and technologies for biomass production and conversion into products. Non-technical aspects refer to actor' organisation, relationships, coordination and governance dimensions. Business model development, management and business strategies are at the interface of technical and organisational aspects.

In the design and development of bio-based value chains and webs, different levels of decision making are interlinked, from strategic level (i.e. long-term decisions), tactic level (i.e. mid-term decisions) to operative level (i.e. short-term decisions) (Espinoza-Pérez et al. 2017; Butemann and Schimmelpfeng 2017). Strategic decision-making plays a crucial role, addressing efficiency, innovation, and implementability of bio-based value chains and webs (Fig. 4.12) (Mertens et al. 2019; Bezama et al. 2019). Additionally, the design must account for the territorial context, recognising the importance of local conditions and resources, while maintaining a strong focus on sustainability. By considering environmental, social, and economic goals (Palmeros Parada et al. 2020; Wohlfahrt et al. 2019; Cardona et al. 2019), a system perspective ensures that bio-based value chains and webs are cohesive, contextually relevant and future-ready.

In the process of designing and developing bio-based value chains and webs, the large variety of combinations between biomass types, processing technologies, and potential products (i.e. biomass-to-products pathways) add complexity for taking strategic decisions such as the selection of regionally implementable value chains. To ensure the imple-

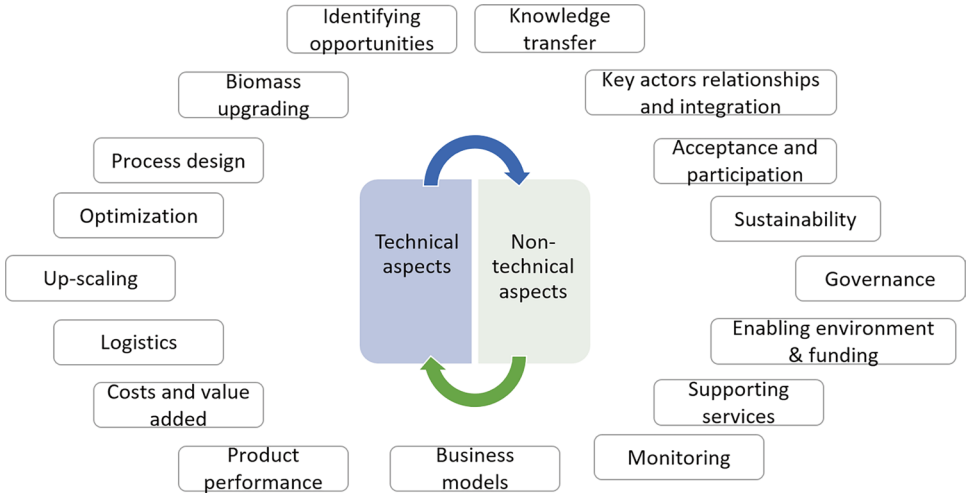


Fig. 4.11 Technical and non-technical aspects that are considered in the design and development of bio-based value chains and webs

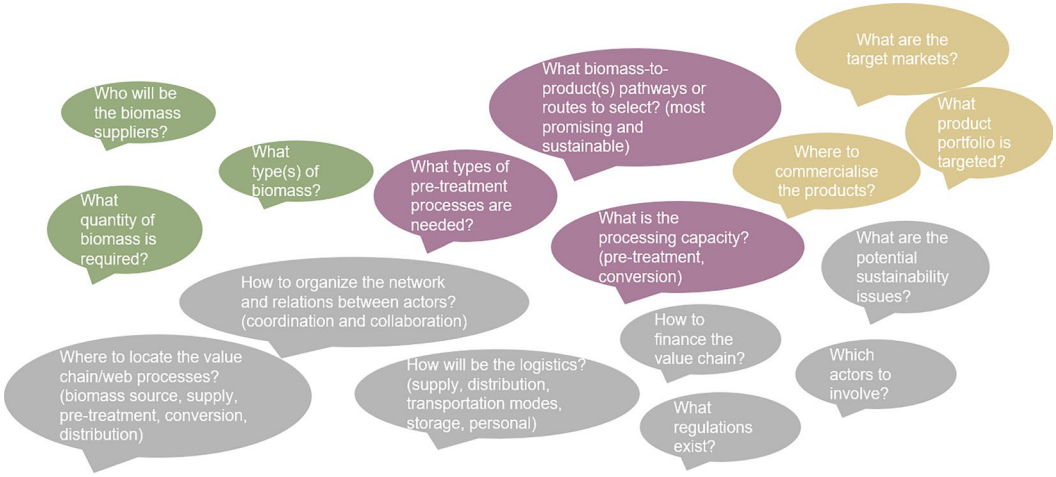


Fig. 4.12 Common strategic questions faced by decision-makers in the design and development of bio-based value chains and webs

mentation of emerging value chains, it is essential to conduct a multidimensional and holistic assessment early in the design and development process, from biomass sourcing to bio-based products. This holistic approach needs to consider territorial/regional conditions (e.g. biomass availability, biophysical constraints, infrastructure, labour, markets, social needs) and properties of processing technologies (e.g. technology readiness level, investment costs, infrastructure requirements and processing capacity) to check the compatibility of the value chain in the region (Vargas-Carpintero 2025; Schlecht et al. 2025). In this way, the integration of technologies and their transformation into practical, implementable solutions can be fostered. As highlighted by Lokesh et al. (2018), once value chains are identified, it is crucial to develop business models that anticipate the interactions among processes, stakeholders and the dynamic nature of the bioeconomy.

Do you want to learn more about the design of bio-based value chains and webs? Take a look at Supplementary Video 4.3, a video from our MOOC "Concepts of Sustainable Bioeconomy" (2021).

4.5.1 Design and Development Approaches

By applying a value chain and web framework, it becomes possible to uncover the socio-economic, biophysical and institutional factors (i.e. territorial/regional context) that influence the performance of these systems, providing a more comprehensive understanding of their dynamics (Virchow et al. 2016; Scheiterle et al. 2018).

A variety of methodologies assist the design and development of bio-based value chains and webs (Fig. 4.13). Conceptual design frameworks and optimisation approaches primarily originated from chemical process design and mainly focused on biorefinery process design (Moncada et al. 2016). They allow for the assessment of raw materials, technologies, products, processing routes through technical, economic, environmental and energy analysis to obtain the best configuration of a biomass-to-product pathway at different stages of development (conceptual design, up-scaling and implementation). Sustainability assessment approaches are also used in bio-based value chain design by applying multi-criteria analysis and comparing different biomass-to-product pathways. Additionally, participatory approaches allow for the involvement of stakeholders in the design process (Vargas-Carpintero 2025; Palmeros Parada et al. 2020). In the practice, researchers and practitioners combine different elements of these methodologies to support the design and development process of bio-based value chains and webs.

The conceptual design approaches involve identifying potential biomass-to-product pathways with techno-economic potential, considering factors, such as the technology and processes required, as well as the stakeholders involved. Techniques like superstructure-based (i.e. combination of alternative biomass-to-product pathways connecting biomass, processes and products) design and mathematical modelling help assess raw materials, processing routes and technologies to determine the optimal configuration of biorefineries, while also incorporating primarily technical, economic, environmental and energy aspects (Moncada et al. 2016; Cardona Alzate et al. 2023).

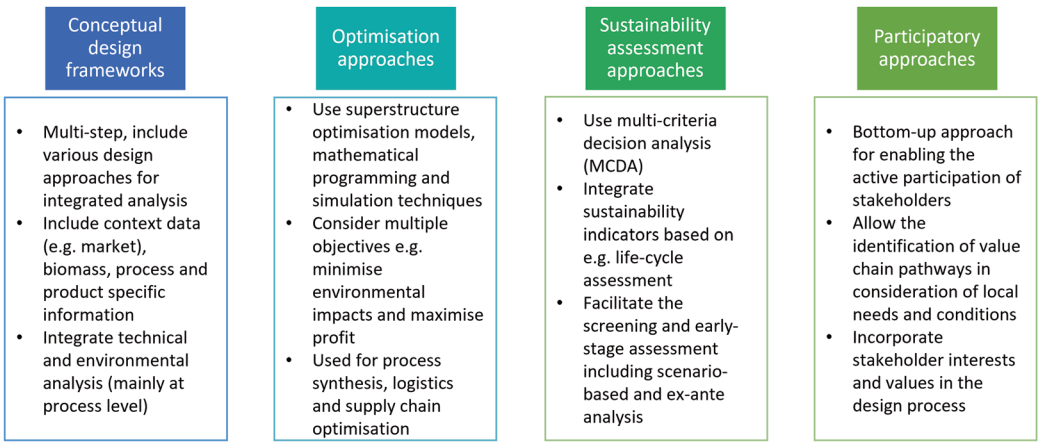


Fig. 4.13 Existing design frameworks and methods in the context of bio-based value chains and webs. (Adapted from Based on Espinoza Pérez et al. 2017; Palmeros Parada et al. 2017, 2020; Aristizábal-Marulanda and Cardona 2019; Benali et al. 2018; Vargas-Carpintero 2025)

Optimisation methodologies focus on improving the performance by employing tools such as linear programming (LP), multi-objective programming (MO), mixed integer linear programming (MILP) and superstructure models to enhance decision-making regarding processing network as well as supply chain optimization. For example, studies have used multi-scale superstructure models to manage biomass pyrolysis supply chains (Sharifzadeh et al. 2015), while others have focused on optimising the economic performance of waste biomass systems (Balaman et al. 2018) or maximising profit in biomass-to-bioproduct supply chains (Abdul Razik et al. 2019).

Early-stage approaches, such as process synthesis methods, allow for quick comparisons of bio-based processes, helping to identify promising biomass feedstocks, processing routes and product portfolios. Similarly, sustainability assessments in early-stage design use multi-criteria approaches to evaluate the environmental, economic, and social impacts of biorefinery systems compared to conventional petrochemical processes, with indicators like economic constraints, environmental impacts, and health and safety risks (Patel et al. 2012, 2013; Posada et al. 2013).

Sustainability assessment approaches usually integrate tools for a multidimensional appraisal of a set of biomass-to-product pathways at ex-ante level or early-stage design but also at implementation level of bio-based value chains (see ▶ Chap. 41). At early stages of design, these methods aim to select those biomass-to-product pathways with best sustainability potential. For this, these methods apply and combine sustainability indicators in multi-criteria decision-making analysis (MCDA). Indicators used are typically related to environmental and technical aspects from holistic assessments such as Life-Cycle Analysis and Techno-Economic Analysis.

Considering the need of contextualizing the design and development process and advancing the integration of social aspects in the design process, bottom-up approaches are being increasingly developed and applied. This is the case of participatory design approaches, which allow for an active involvement of stakeholders in the design process, in the definition of objectives of a bio-based value chain project and in the incorporation of local stakeholders' interests and values (Palmeros Parada et al. 2020). These methods can increase the social acceptability of novel bio-based value chains while being steered towards the actual needs and conditions at the local level.

4.5.2 Integrating Design and Development Tools with a Territorial Approach

Existing methods for technical design of biorefinery systems provide a suitable set of tools for the planning of bio-based value chains and webs. Combining these methods with participatory approaches can favour the design and development process by including stakeholder's visions and perspectives, which adds a relevant layer of reality conditions for developing a value chain project. The need of more inter- and transdisciplinarity for setting value chains becomes imperative, considering that value chain design and development are tasks that involve technical knowledge but also actors' organisation and the acceptance of stakeholders to get involved. The regional implementation potential of these systems largely depends on local actors, and incorporating their perspectives and needs into the design process is crucial for ensuring the practical implementation and success of bio-based value chains.

Research in new biomass production systems, processing technologies and products set a portfolio of options with technological potential to set new value chains. But are all these solutions implementable? What could be needed for these technologies and value chains to be implemented in economic sectors? Adaptive and reflexive processes for the design and development of bio-based value chains help to continuously consider conditions and criteria to jump from 'technological potential' to 'implementation potential'. A framework conceptualised by Vargas-Carpintero (2025) contributes to this challenge by integrating

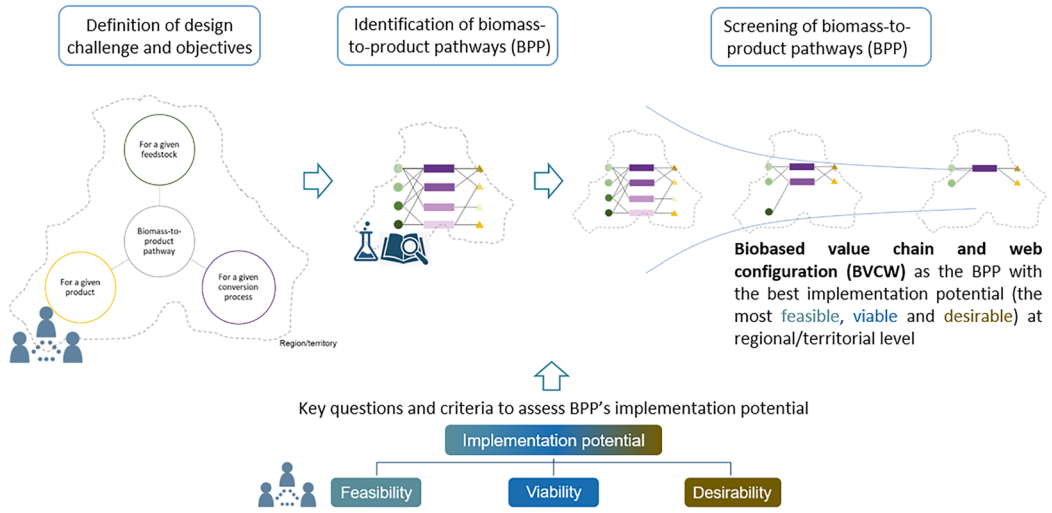


Fig. 4.14 Integrated approach for bio-based value chain and web design. (Vargas-Carpintero 2025 licensed under CC BY 4.0. ▶ https://creativecommons.org/licenses/by/4.0/)

key generic steps in the design process based on existing approaches—(i) definition of design challenge and objectives; (ii) identification of biomass-to-product pathways; (iii) screening biomass-to-product pathways, using a multi-criteria set (Fig. 4.14).

For a bio-based value chain and web configuration (i.e. biomass-to-product pathway) to be implementable, it is necessary to check its compatibility with the surrounding context (external view) and within the production system (internal view). For this purpose, three performance assessment dimensions are defined, following the rationale of design thinking and system analysis (Giampietro 2023; Bocken et al. 2022): (i) *feasibility*, to check the compatibility of the bio-based value chain with the biophysical context (is it environmentally feasible?); (ii) *viability*, to check its compatibility with techno-economic constraints (is it techno-economically viable?); and (iii) *desirability*, to check its compatibility with societal norms, values and institutions (is it socially desirable?).

The first dimension, feasibility, encompasses aspects related to the availability of natural resources, ecosystem services and ecological boundaries of the biosphere. The second dimension, viability, covers aspects associated to technical potential such as technology readiness and technology performance, as well as economic factors such as production costs and market access. The third dimension, desirability, explores the social acceptability and the suitability of the system with the institutional and regulatory framework, encompassing aspects such as social acceptance, regulatory compliance and food security (see ▶ multi-criteria set, https://ars.els-cdn.com/content/image/1-s2.0-S0926669024020818-gr7_lrg.jpg). The application of the integrated framework in value chain R&D projects strengthens bio-based value chain and web design by combining process engineering, territorial context, and multi-actor approaches to evaluate feasibility, viability, and desirability (Vargas-Carpintero 2025; Schlecht et al. 2025). Its operationalisation requires the incorporation of measurable indicators associated to the multi-criteria set and regionalised analyses, enabling more comprehensive and comparable assessments of implementation potential across different biomass-to-product pathways, as illustrated in Schlecht et al. (2025) for value chains from novel crops grown on marginal lands for industrial purposes in Europe. In order to facilitate the usability of the framework, a set of check questions for each of these dimensions is presented in Fig. 4.15, derived from the multi-criteria set. These exemplary questions serve as a checking tool for researchers and practitioners in the assessment of

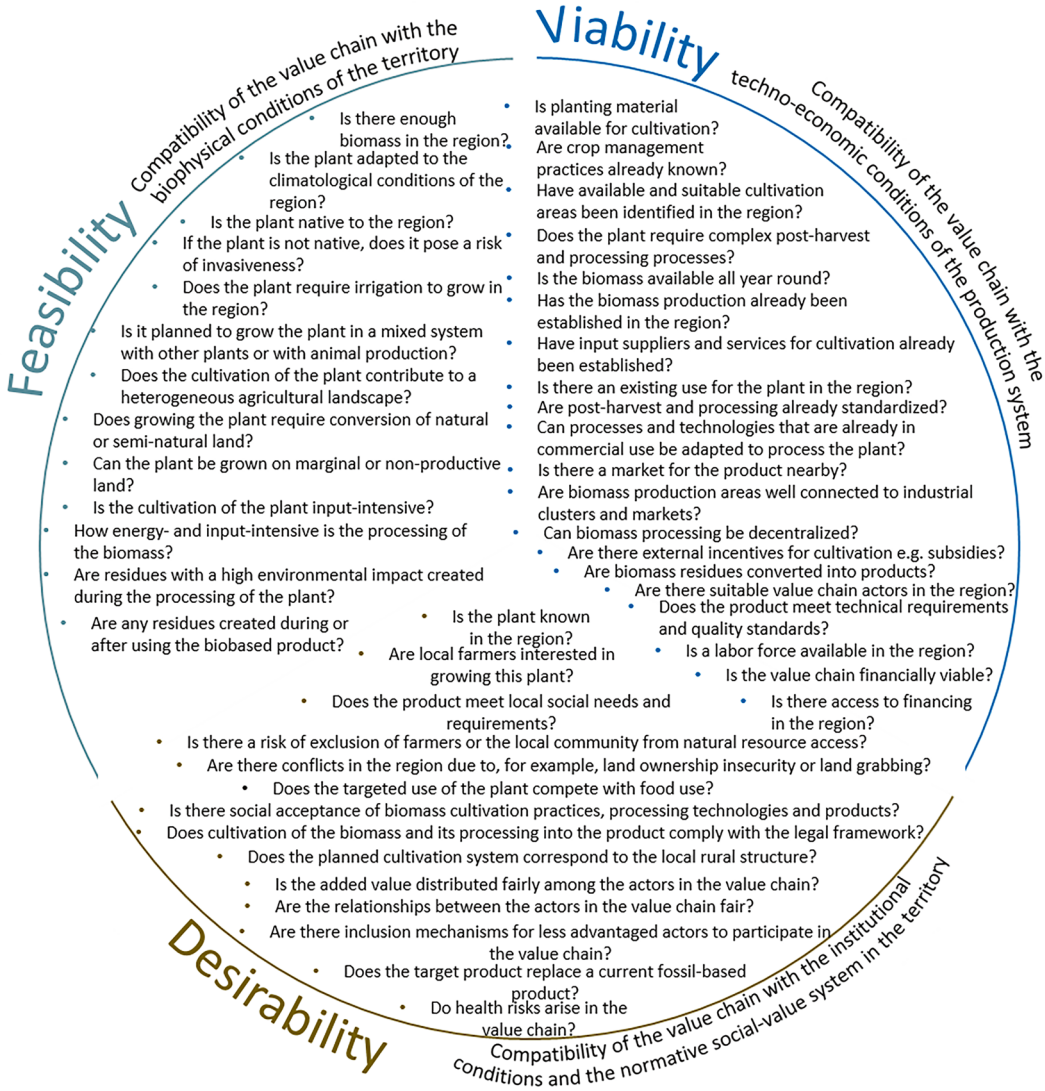


Fig. 4.15 Exemplary check questions to assess the implementation potential of bio-based value chains and webs from plant-based biomass. (Based on Vargas-Carpintero 2025)

biomass-to-product pathways and the improvement of the implementation potential (Vargas-Carpintero 2025; Schlecht et al. 2025). The questions are defined for plant-based biomass (e.g. novel crops) and can be adapted to other biomass types and cases.

In the following chapters, a variety of technological approaches and concepts related to biomass production and supply, processing and products are introduced. These are the key building blocks for the creation of new bio-based value chains and webs. Along these chapters, we encourage you to reflect on the concepts and methodological approaches presented in this chapter, the characteristics of bio-based production systems and the variety of aspects, technological and organisational, as well as stakeholders that need to be considered in the process of designing and developing these systems to ensure their sustainable implementation. The value chain concept serves in this process as an appropriate framework to connect the pieces of the large puzzle of the bioeconomy system.

Questions

1. What are the building blocks of bio-based value chains and webs?
2. What are the advantages of extending the concept of bio-based value chain to value webs?
3. What are key characteristics of bio-based value chains and webs?
4. What examples of strategic questions in the design of bio-based value chains and webs can be mentioned?

Answers

1. The main building blocks or parts that make up bio-based value chains and webs are biomass production, biomass processing, and bio-based products and markets, along with actors, processes, inputs and outputs, supported by ecosystem services, institutions and further value chain actors.
2. The bio-based-value web allows to analyse the interrelation, linkages and synergies opportunities between several value chains, to account for the variety of biomass valorisation pathways and identify possibilities for increasing productivity while contributing to sustainability.
3. Bio-based value chains and webs rely on biomass as renewable resource for their operation, are highly complex due to intrinsic characteristics of biomass (e.g. seasonality, composition, geographic distribution), account for multiple biomass uses, are multi-product systems suitable to integrated processing (e.g. biorefinery), are embedded in territories and are shaped by contextual factors, involve multiple stakeholders, sectors and multi-dimensional aspects (e.g. environmental, socio-economic, institutional, cultural), pursuit sustainability performance by design and demand a strong knowledge base and innovation processes.
4. Examples of strategic questions include: what type of biomass to select?; where is the biomass supply from?; what processing scale should be considered?; what type of processing technology to select?; which markets to target?; what product portfolio to offer?; who will be the stakeholders?; what sustainability impacts would be created?; and where to locate the value chain processes?

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Biomass Production Systems

The bioeconomy makes use of two types of resources: (**1**) biomass, originating directly or indirectly from plants, microorganisms or animals, and (**2**) biological knowledge. Bioeconomists require knowledge of these resources in order to plan the resource supply strategy for a given bioeconomic activity, decide which biomass resource is best suited for a particular bio-based product chain, and identify how these product chains can be optimised. This part describes the origin and characteristics of biomass and bio-based resources, as well as the mechanisms of the primary biomass production systems in agriculture, forestry and the blue bioeconomy. It also looks at urban agriculture, microalgae production and insect farming and describes the supply of bio-based resources derived from residual biomass and biogenic wastes, including the production of bio-based fertilizers. It goes on to describe the evolution of and current trends in digital agriculture, in particular the integration of artificial intelligence (AI) into agricultural technology. This part concludes with the economics of primary production, which are characterized by the specifics of biological production systems with seasonal variations and the requirements of long-term planning.

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Bio-Based Resources

Christian Zörb and Iris Lewandowski



Fig. 5.0 Bio-based resources. (© Ulrich Schmidt) (▶ https://doi.org/10.1007/000-htf)

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This chapter describes the nature of the two bioeconomy resources: biomass and biological knowledge. Biomass is primarily produced in the process of photosynthesis, which is described in the first part of this section. In this process, CO_2 and water are converted into carbohydrates by autotrophic organisms using energy from sunlight. How well plants perform in this process of converting light energy into chemical energy through the incorporation of carbon (C) into their substance depends on many factors, including climate and soil properties. The resulting biomass can be characterized by its origin (plants, animals or microorganisms), the sectors in which it is produced, its main components or its physical state. The third part of the chapter describes how these biomass characteristics can be improved or designed through breeding. It explains the principles of breeding, green biotechnology, genetic engineering and synthetic biology. These are all technologies that are applied when biological knowledge is used. Biological knowledge is described in the fourth part of the chapter. It is the combination of biological data and the interpretation of their meaning. Elements of biological knowledge include 'omics' for learning from large data sets, conventional and molecular biotechnologies, and bionic and biointelligence approaches. Practical examples for so-called nature-based solutions, that is, solutions inspired and supported by nature, are described in the fifth section. The chapter concludes with a global view on primary biomass production and land resources and how to assess biomass availability.

Learning Objectives

After studying this chapter, you will…

- …be able to explain the process of biomass formation (see ► Sect. 5.2).
- …be able to characterize the resource base of the bioeconomy (see ► Sect. 5.2).
- …be able to outline techniques to design biomass characteristics (see ► Sect. 5.3).
- …be able to explain the concept of biological knowledge (see ► Sect. 5.4).
- …be able to describe nature-based solutions (NbS) and their application (see ► Sect. 5.5).
- …be able to explain how one may assess the availability of biomass (see ► Sect. 5.6).

Bio-based resources are of biological origin and contain non-fossil, recently (<100 years) derived organic carbon biomass from living or formerly living organisms (see ► Sect. 1.2). Before describing the origin of biomass, we show how different the perspectives on biomass can be.

5.1 Biomass Concepts—Different Perspectives

The concept of biomass was introduced in 1927 in a publication by the German zoologist Reinhard Demoll (1882–1960): 'By biomass we term the quantity of substance in living organisms per unit of surface or volume' (Demoll 1927). There is currently no consensus on a general definition of biomass. A simple and widely used biological definition is: 'organic matter derived from living, or recently living organisms'. This definition may be too broad to be useful as a precise definition for this bioeconomy textbook. Let us focus on different perspectives of what constitutes biomass. Even in ecology, there is no standard definition of biomass. One reason for this is that biomass changes as organisms interact with each other and with their abiotic environment. Instead, a colourful variety of ecological biomass concepts exist side by side.

A Biologist's Perspective

When considering the term 'biomass', a biologist would first think of carbohydrates (e.g. starch, sugar), proteins (e.g. storage proteins from grains), fats and oils (e.g. from oilseeds) and other secondary plant compounds. These substances are all secondary metabolites of (plant) tissues, many examples of which can be found in biochemistry textbooks. Primary plant metabolites are compounds produced from the

sugars formed by photosynthesis and used for metabolism. Secondary metabolites by contrast are not involved in primary metabolism but are responsible, for example, for the structure and functioning of a cell or organism. Higher plants probably build around 100,000–150,000 different secondary compounds including a diverse range of proteins, sugars, sugar alcohols, vitamins, fats, oils, amino acids, organic acids, nucleic acids, phenolic compounds, odours, pigments etc. There are many interesting substances within these classes that may be (re) discovered in the bioeconomy as valuable compounds for polymer chemistry, or possibly even pharmacy.

A Chemist's Perspective

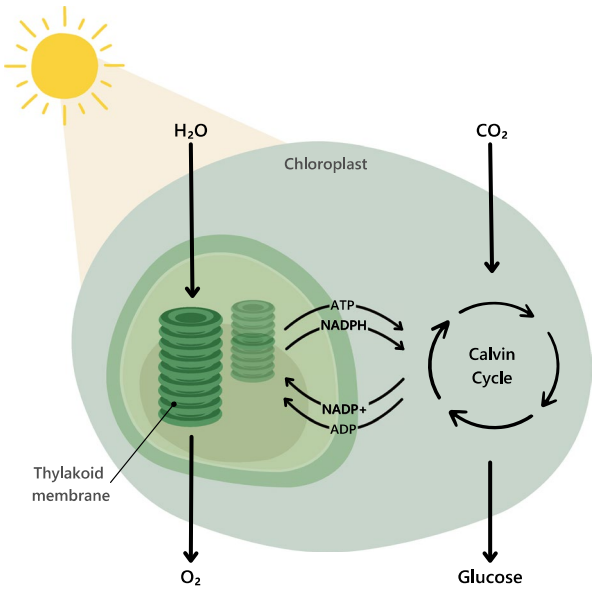
A chemist would like to see a general molecular formula to describe carbohydrates, proteins, fats and other secondary substances showing the chemical elements incorporated by autotrophs (see ◘ Fig. 5.1 and photosynthesis below) together with an amount of binding energy. Unfortunately, however, there is no chemical formula for the general definition of biomass. Physicists or agronomists may calculate the energy value of a given biomass fraction, from a field of maize for example, using an equation for the heating value of biomass based on its components, but this is also only part of the 'what is biomass?' story.

A Technologist's Perspective

Technologists see biomass as a source of energy. For this reason, they tend to think of plant-based materials that are not used for food or feed applications, specifically lignocellulosic biomass. Although technical definitions of biomass only include biotic substances that can be used as energy sources, a number of different energy-related biomass terms and definitions still exist. Biomass can be used for energy either directly via combustion to produce heat, or indirectly after conversion into various forms of biofuel. There are several methods of converting biomass into biofuels and these are broadly classified as thermal, chemical or biochemical (see ▶ Chaps. 18, 19 and 24 for a description of conversion technologies).

Our Definition of Biomass

In ▶ Sect. 1.2, bio-based resources were defined as all resources containing non-fossil, organic carbon, recently (<100 years) derived from living plants, animals, algae, microorganisms or organic waste streams. These are



Photosynthesis reaction:

$$6\,CO_2 + 6\,H_2O \xrightarrow[Chlorophyll]{Light} C_6H_{12}O_6 + 6\,O_2$$

CO_2 = Carbon dioxide
H_2O = Water
$C_6H_{12}O_6$ = Glucose
O_2 = Oxygen

◘ **Fig. 5.1** The process and chemical equation of photosynthesis

summarized under the term 'biomass'. Biomass can be further defined as: plant or animal tissues or tissue-based materials, microorganisms and the substances produced by them, as well as organic molecules formed (primarily) by (photosynthetic) organisms such as carbohydrates (e.g. sugars), proteins, fats, fibres, vitamins and other secondary plant metabolites. This includes edible biomass, such as protein-, starch-, sugar- and oil-rich biomass, as well as non-edible lignocellulosic biomass from dedicated crop production, residues and organic wastes. Today, the term 'biomass' is most frequently used to refer to organic material utilized for energy production and other non-food applications such as the production of biogenic materials and chemicals. In the following text, we use a more general definition of biomass, which includes both edible and non-edible organic material.

> ***Biomass*** refers to plant or animal tissues or tissue-based materials, microorganisms and the substances produced by them, as well as organic molecules formed (primarily) by (photosynthetic) organisms such as carbohydrates (e.g. sugars), proteins, fats, fibres, vitamins and other secondary plant metabolites.

5.2 Biomass: Its Origin and Characterization

Photosynthesis

Primary production is the process that directly or indirectly supports virtually all life on Earth. Primary biomass is formed by the conversion of carbon dioxide (CO_2) and water through the autotrophic processes of photosynthesis (performed by plants and green algae) and chemosynthesis (performed by some microorganisms). Of these two processes, photosynthesis is the more important. In this process, autotrophic organisms take up CO_2 and water and convert them into carbohydrates with the help of light energy (photons). In this way, light energy is converted into chemical energy through the incorporation of carbon (C) into the organism's substance (assimilation). The final products of photosynthesis are C6 sugars (hexoses) and oxygen. Figure 5.1 shows the chemical equation as well as a rough scheme of the complete process.

Glucose is used as a resource in internal plant biochemical processes to form various other molecules through subsequent biochemical reactions that also incorporate macro- and micronutrient elements into the plant substance. It is estimated that plants are capable of producing some 100,000 to 150,000 different chemical compounds, many of which have not yet been identified but could be of interest in a future bioeconomy. However, not all of these substances are available in sufficiently high quantities or concentrations. Biotechnological methods may make it possible to increase the production and concentration of target molecules by plants and microorganisms.

The first step in biomass formation is the absorption of light by the chlorophyll molecule. Photosynthetic electrons are used for the assimilation of CO_2 and the formation of carbohydrates such as sugars in plant cells. However, not all of the absorbed energy electrons can be converted into chemical energy in the form of sugars. There are energy losses in the process of photosynthesis, for example, the heat produced by metabolism, and energy consumption through photorespiration and other processes such as the Mehler reaction (for further information, see Taiz et al. 2015). Therefore, the maximum efficiency of photosynthesis is estimated to be about 12%. However, this is a theoretical maximum (Radmer and Kok 1977) that can never be achieved by a growing plant, even if all adverse factors such as disease, predation, inadequate inorganic nutrient supply and suboptimal water supply are mitigated. Wilhelm and Selmar (2011) calculated a conversion efficiency of photosynthetic energy to biomass of only about 8% (Fig. 5.2).

In view of the above-mentioned energy losses in biomass formation, it is of vital importance that available biomass is used as efficiently as possible. Here, three approaches

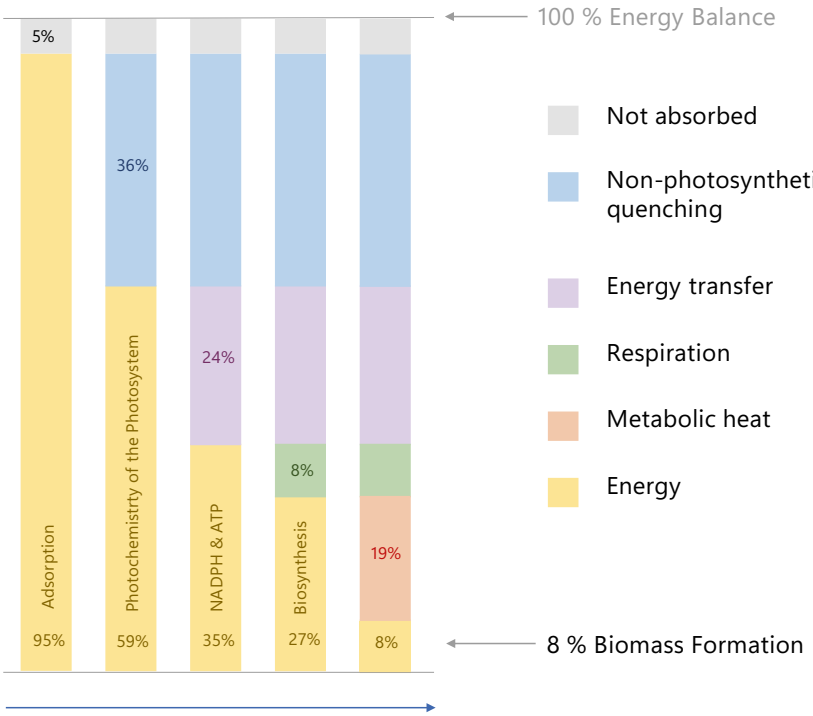


Fig. 5.2 Energy balance of biomass production. (Based on Wilhelm and Selmar 2011). Bars represent photosynthetic energy absorbed and the various energy losses by transformation into biomass. 100% is the maximum photosynthetic active energy

to the efficient production and use of biomass are suggested:

- Focusing on the production of valuable (biochemical) substances by plants and algae. An effective strategy would be the production of valuable organic substances (such as glycolate, omega-3 fatty acids, lutein) by algae. Microalgae (▶ Chap. 10) in particular have a higher photosynthetic efficiency because the light absorption of small algal cells (unicellular algae) is generally better than that of larger algae.
- Supporting the efficiency of crop production through optimal crop management, improved harvest technologies and the avoidance of biomass losses in the supply chain (see ▶ Sect. 6.11.5)
- Applying breeding and biotechnological methods to supply varieties that make optimal use of the factors necessary for growth and are tailored to the production of specific products (e.g. metabolites, proteins) at high concentrations in the biomass.

All biological material (or biomass) is essentially derived from inorganic molecules or ions that are assimilated into the biological tissues of autotrophic (primary) organisms (plants and microorganisms) through photosynthetic or chemosynthetic processes. Organisms that perform primary production are called 'autotrophs' because they are self-feeding and use light as an energy source. In the process of photosynthesis, they take up CO_2 and convert it into chemical energy with the help of sunlight. These organisms provide the basis for secondary biological organisms, that is, heterotrophs. Heterotrophs (animals, humans, fungi, most bacteria) rely on the consumption of either the products of autotrophs or whole autotrophic organisms.

Biomass is formed primarily from carbon (C), oxygen (O) and hydrogen (H) (Fig. 5.3). These are assimilated from air and water. In addition, mineral macronutrients are essential for plant growth and development and thus biomass formation. The main macronutrients necessary for the production of biomass by

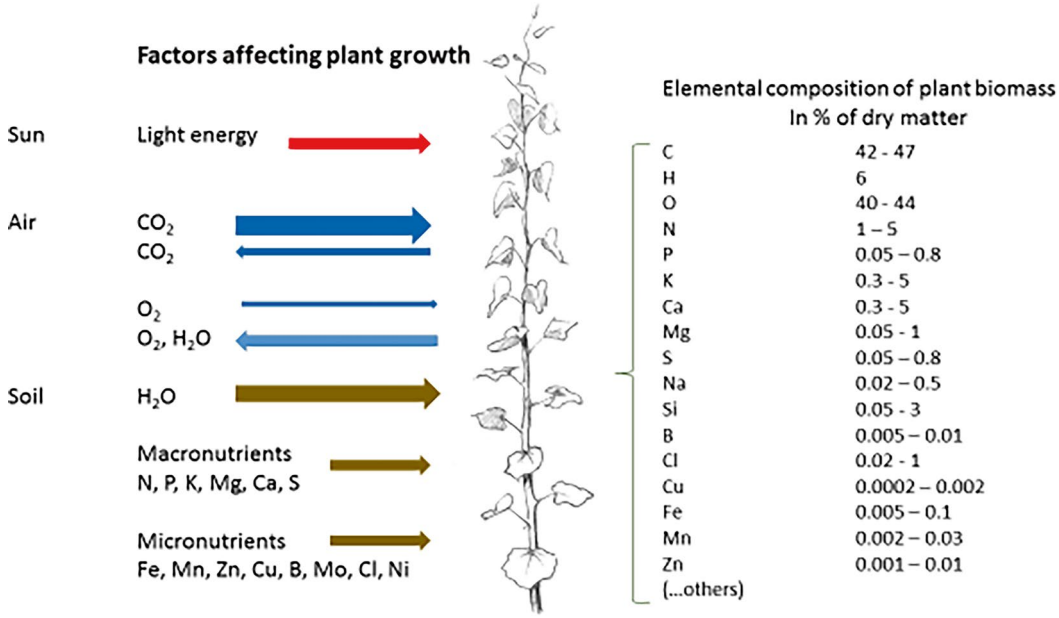


Fig. 5.3 Factors affecting plant growth and elemental composition of plant biomass. (Adapted from Lewandowski and Wilhelm 2016)

primary organisms are: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S). These elements are also the major components of plant fertilizers, mostly in the form of ammonium, nitrate, urea, phosphate and potassium salts. Other important elements are the so-called plant micronutrients, which are essential but only in very small quantities—mostly at concentrations three orders of magnitude lower than those of macronutrients. They include iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), chlorine (Cl) and nickel (Ni). Other elements that can be beneficial for plant growth in niche environments are silicon (Si), cobalt (Co), selenium (Se) and sodium (Na).

Biomass Characterization

Biomass resources can be classified according to their origin, that is, whether they come from plants, animals or microorganisms. Not only the requirements for their production, but also the characteristics of their products differ. This is not only relevant from a processing point of view, but also from an ethical point of view, for example meat is not an 'acceptable' biomass for vegetarians.

Biomass resources can also be classified according to the sector in which they are produced, for example, as agricultural, forestry or waste biomass (Fig. 5.4). The biomass supply chains in each sector vary from a practical point of view. However, also from an ethical point of view, it makes a difference whether biomass has been classified as waste or whether it comes from the agricultural sector. The use of waste biomass is generally considered beneficial, whereas agricultural biomass has the primary task of producing food. In the latter case, a careful decision needs to be made on the best use of the biomass to avoid competition with the food supply (see ▶ Sect. 17.1). The energetic use of edible biomass, such as vegetable oil, for the production of biofuels has received particular criticism. For this reason, biomass is also classified into 'edible' and 'non-edible' with respect to its suitability for human consumption. Thus, biomass can also be classified according to its anticipated use (Fig. 5.6).

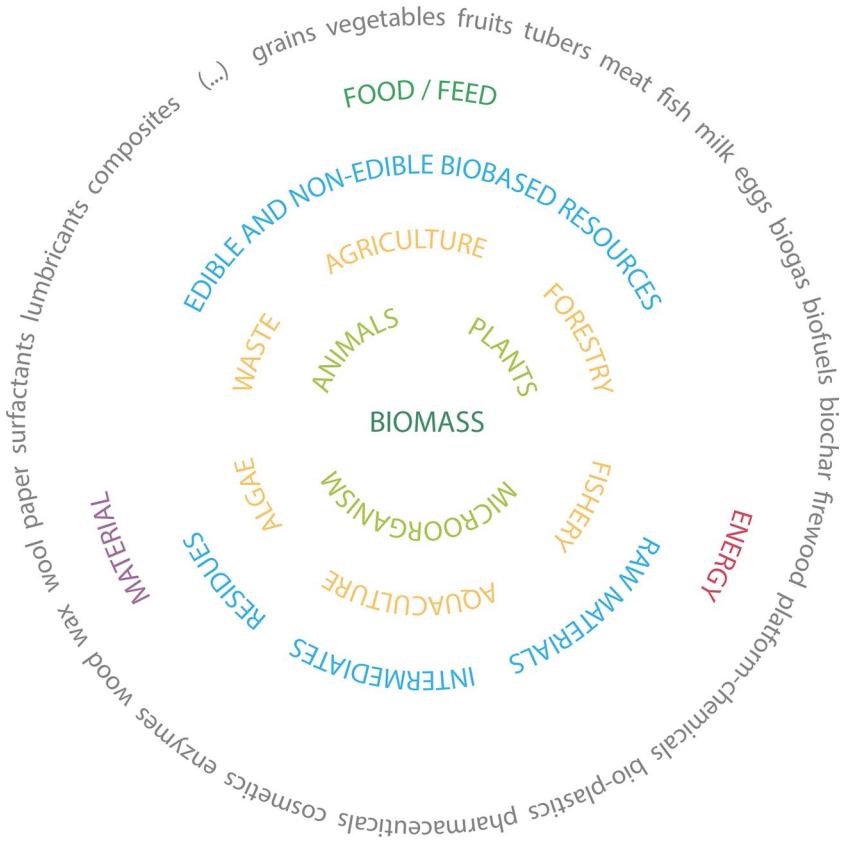


Fig. 5.4 Bio-based resources. Plant, animal, and microorganism biomass is produced in different primary sectors of the bioeconomy. These biomass resources are processed into food, feed, energy or raw materials. Examples of products used in the bioeconomy are seen in the outer circle

The most relevant classification of biomass for its integration into specific bio-based product chains is according to its main components, that is, starch, sugar, lignocellulose (lignin + cellulose + hemicellulose), oil or protein (Table 5.1). All of these contain mainly C, H and O. Only proteins, being a combination of different amino acids, also contain N and some contain S (Table 5.1).

Figure 5.5 shows the main components of different biomasses. These vary considerably between lignocellulosic biomasses (such as wood and straw), starch-rich biomasses (e.g. wheat grain), oil-rich biomasses (e.g. rapeseed), sugar-rich biomasses (e.g. sugar beet) and protein-rich biomasses (e.g. pork and fish).

Finally, biomass can also be characterized according to its physical state into 'wet' and 'dry' or 'solid' and 'liquid' biomass (Fig. 5.6). The physical properties of biomass determine the requirements for its harvest, transport, storage and processing. In general, wet biomass is more perishable than dry biomass. It requires a higher transport effort (because more water is transported) and additional processing before storage, such as drying or ensiling (e.g. maize is ensiled for feed and biogas applications).

Global Biomass Use

It is currently estimated that about 11.4 billion tons of biomass are produced annually on agricultural land and in forests. Of this,

Table 5.1 Classification criteria for biomass resources

Organisms which produce biomass	Sector of biomass production	Major biomass components (molecular formula)
Plants Animals Microorganisms	Agriculture Forestry Fishery and aquaculture Algae and microorganisms Waste	Sugars (e.g. glucose: $C_6H_{12}O_6$) Starch $(C_6H_{10}O_5)_n$ Cellulose $(C_6H_{10}O_5)_n$ Polysaccharides, such as hemicelluloses consisting of different monosaccharides (e.g. xylose: $C_5H_{10}O_5$) Lignin (cumaryalcohol: $C_9H_{10}O_2$, coniferylalcohol: $C_{10}H_{12}O_3$, sinapylalcohol: $C_{11}H_{14}O_4$) Oils (triglycerides, e.g. oleic acid: $C_{18}H_{34}O_2$) Proteins (amino acids, e.g. alanine: $C_3H_7NO_2$)

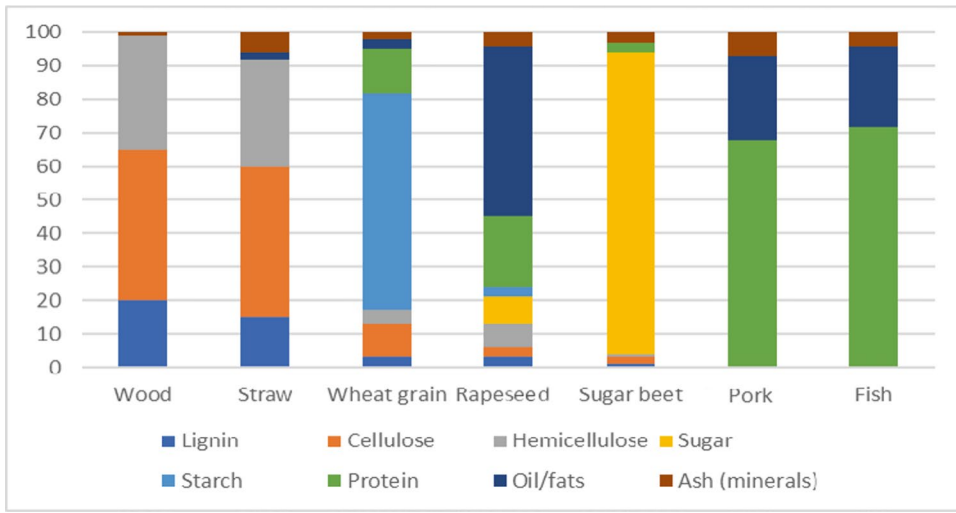


Fig. 5.5 Main components of different biomasses (dry matter)

18% stems from wood, 40% from agricultural production, 30% from pasture and 12% are by-products (FAOSTAT 2014; Raschke and Carus 2012). The largest part of this biomass is comprised of cellulose (5.62 billion t, 49%). Other important biomass feedstocks are sugar/starch (2.63 billion t, 23%), protein (1.23 billion t, 12%) and fat (0.51 billion t, 4%) (FAOSTAT 2014). About three quarters of the total biomass produced by agriculture is used as feed to produce 115, 90 and 60 million tonnes of pork, chicken and beef, respectively, and 640 million litres of milk (Fig. 5.7).

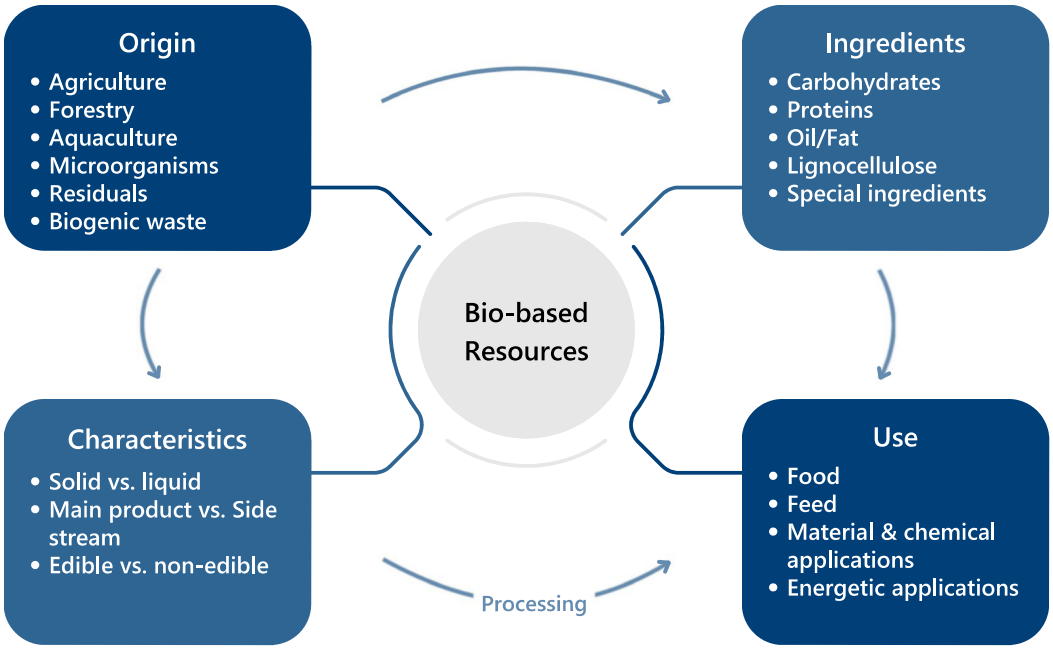


Fig. 5.6 Classification of bio-based resources, including biomass origin, components and diverse physical and general characteristics

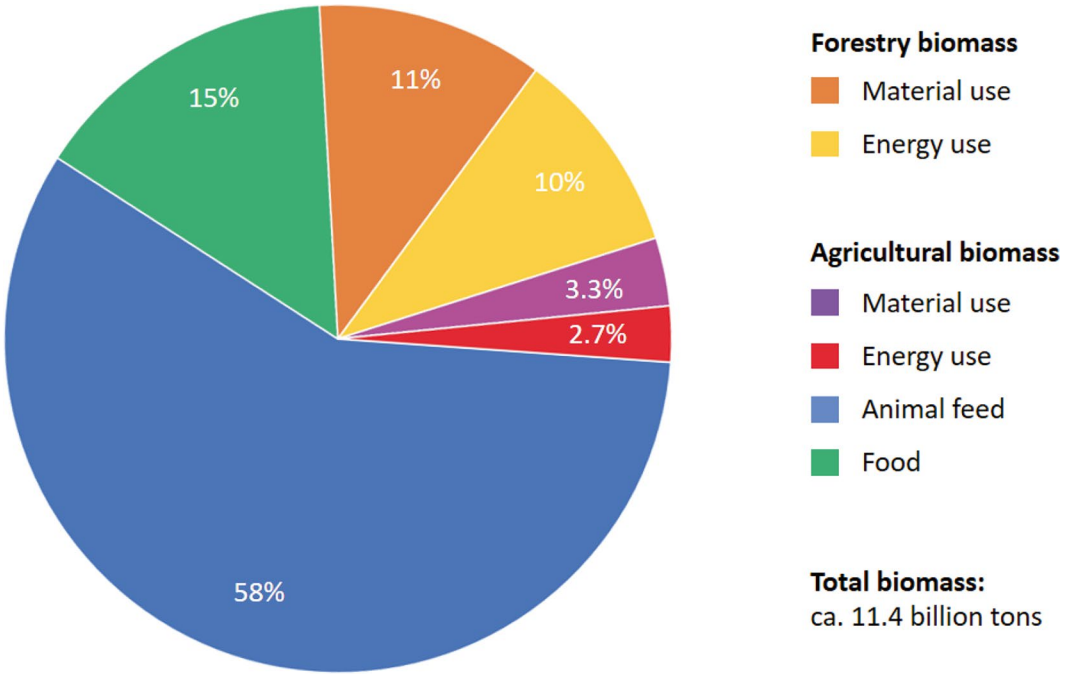


Fig. 5.7 Worldwide use of harvested forestry and agricultural biomass in 2008. (Based on Raschke and Carus 2012)

5.3 Techniques for Improving or Designing Biomass Characteristics

Breeding

Humans started to cultivate plants when they began to settle about 10,000 years ago. It was beneficial for them to have food stored throughout the whole year, to consume when less or no freshly produced food was available. This enabled them to survive in unfavourable climates where naturally grown plant-based food was only available in a particular season. Early farmers began breeding wild plants and selecting the genotypes with the best performance in terms of high yield, non-shedding seeds, and resistance to biotic and abiotic stress (e.g. drought). They developed many of our most important crops, such as wheat, maize (corn), oilseed rape and rice. Today, breeding progress is still the most important prerequisite for sufficient and sustainable food production.

Breeding is the improvement of crop varieties and animal breeds—in terms of yield, resistance to pests and diseases, fertility, product quality or adaptation to different production conditions—through breeding methods. These are classified as either 'conventional' or 'genetic engineering' or 'gene editing' methods. Conventional breeding aims to provide improved varieties or breeds through selection and directed crossing. Genetic engineering (or genetic modification) uses biotechnological techniques to alter the genome (genetic material) of the organism and gene editing uses the CRISPR-Cas technique to make small changes such as deletion of amino acids or nucleotide changes in the DNA of the species. An example of this might be the deletion of one base pair in the S gene DNA of a crop plant to reduce its susceptibility to a pathogen (e.g. a mildew fungus). Whether this technology should be considered as genetic modification or gene editing, or not subject to any regulations is debatable.

Green Biotechnology

Biotechnology is 'any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use' (UN Convention on Biological Diversity, Art. 2). Green biotechnology is the application of such techniques in agricultural processes. An example is the use of genetic engineering methods to design ▶ transgenic plants or gene-edited plants capable of growing in particular environments characterized by the presence (or absence) of specific (bio-)chemicals.

DNA (Deoxyribonucleic acid) carries the genetic information of living organisms and is therefore essentially the blueprint of an individual. DNA is a double helix formed by base pairs attached to a sugar-phosphate backbone.

A ***gene*** is the basic physical and functional unit of heredity passed from parent to child. Genes are made up of sequences of DNA. Genes are arranged, one after another, at specific locations on chromosomes in the nucleus of cells. Each chromosome contains many genes.

The ***genome*** is the complete set of DNA instructions found in a cell. In maize (*Zea maize*), the genome consists of 10 pairs of chromosomes located in the cell's nucleus and one small chromosome in the cell's mitochondria. A genome contains all the information needed for an individual to develop and function.

A ***transgenic plant*** is one whose DNA has been modified by genetic engineering. This means that one or more genes from another species have been introduced and combined with the plant's genetic material to change the characteristics of its original

genome. It is a matter of debate whether gene editing, such as deleting a (small) portion of DNA via CRISPR-Cas, should be considered genetic modification or not be subject to any regulations.

Genetic Engineering

Genetically modified organisms (GMOs) are organisms that have had their genomes altered, either in a way that does not occur naturally or in a natural but accelerated way. To produce a GMO, specific characteristics can be changed using laboratory techniques to delete or modify particular sections of DNA (deoxyribonucleic acid: contains the genetic information, for example, genes and regulatory elements). An organism's characteristics can also be altered by introducing new pieces of DNA into its genome. These can originate from the same species or another, unrelated species. The latter results in a transgenic organism, that is, one that contains genes from a different species. Progress in breeding tends to be faster and more specific when biotechnological methods are used. There is also debate as to whether a gene deleted or added from within the family of the same species should fall under the regulations for GMO's or not.

Genetic modification or gene editing techniques can be applied to crops to alter the chemical structure of polymers, such as starch, lignin or other fibres to improve industrial production processes. It is also possible to modify proteins or metabolites for use in the chemical, construction or pharmaceutical industries. The use of plant antibodies against human or animal diseases has been applied in practice for three decades. The advantage of using GM crops for pharmaceutical purposes is that the agents can be produced in greenhouses or fermenters, and official regimentation is much lower than for field trials. Most varieties of a number of major crops, including soybean, maize and cotton, commonly grown in the US, Brazil, China, India and elsewhere, have been genetically modified. However, GM crops are usually not well accepted by the general public, and in Europe their production in the field is very limited or non-existent. In addition, GMO production is not permitted in organic agriculture. The CRISPR-Cas9 gene-editing technique used in plant breeding is a biotechnological method to cut out (knock out) genes without leaving a trace or to specifically alter or add genes or gene fragments to introduce desired traits. The status of crop varieties produced by this method is currently the subject of debate. The question is whether these organisms should still be considered genetically modified if only parts of the genes have been cut out or altered without introducing genetic material from other organisms, or if genetic material from other species was only temporarily introduced for intermediate breeding steps (e.g. early flowering in trees) and then removed again.

Breeding and genetic modification can be categorized according to the nature of the traits conferred. Input traits are those that affect crop performance without changing the nature of the harvested product. Examples include resistance to pests, viruses, bacteria, fungi or insects; tolerance to abiotic stresses (e.g. soil-borne metals, salinity, drought, heat); and increased nutrient use efficiency resulting in higher biomass yields.

Output traits change the quality of the crop product itself, e.g. by altering the starch, protein, vitamin or oil composition to improve the nutritional value. This can be, for example, through an increase in vitamins, omega-3 fatty acids or antioxidants, a decrease in saturated fats, or an improved amino acid balance. Other output trait targets include enhanced levels of essential minerals (Fe, Zn), elimination of allergenic proteins, improved taste, longer shelf life and the introduction of novel food products. Output traits may also focus on the (small-scale) production of biomass for biopharming, sold at a premium price.

Synthetic Biology

Synthetic biology goes beyond the application of existing biological mechanisms and knowledge. It uses the tools of genetic engineering and biotechnology to construct completely new, non-naturally occurring biological functional units or systems with desired properties, or to redesign existing biological systems

for new tasks (Kircher et al. 2017). For example, recent technological advances have enabled scientists to produce new DNA sequences from scratch. Through the application of modern engineering principles and use of computers and chemicals, organisms can be designed that are suitable for technical purposes, for example, the direct production of biofuels or precursor chemicals for pharmaceutical drugs. Synthetic biology offers new opportunities in the bioeconomy, for example, to supply products that cannot be produced economically through chemical processes or for which there are no natural synthesis methods (Kircher et al. 2017).

5.4 Biological Knowledge

The discipline of biology was established around 1800 as the 'science of life'. Biological research produces large sets of data at different scales, ranging from genetic information to biodiversity and the interactions between species, landscapes and climates. Biological knowledge is the combination of biological data and the interpretation of their meaning. Traditionally, such data were interpreted by humans, but today, due to the sheer volume of data, the interpretation of large-scale data sets is only possible with the help of computers. This is mostly done by bioinformatics—the use of computational and mathematical techniques to store, manage and analyse biological data (Kaminski 2000). A major area of bioinformatics application or artificial intelligence (AI) tools is the analysis of DNA and protein sequences and structures to characterize the functions associated with them. The term 'omics data' is also used to refer to this type of bio-information. There are data available for genomics, proteomics, metabolomics, ionomics and several other '-omics'. The term 'big data' is also used to refer to large quantities of biological data but can also be applied to areas other than genetic information, such as data for analysing human health and interactions with various factors, including nutrition and the environment. Omics data are often used for breeding purposes, for example, for the identification of genes that code for important traits such as crop resistance to pathogens, animal health or quality parameters. Big data sets can also be used, for example, to describe the pharmacological relevance of particular substances, for example, those produced by plant cultures, either GM or conventional. This is of great value for a knowledge-driven, bio-based economy, because it can help provide practical information for developments in the production of medicinal plants and food crops. One example is the use of bio-based genomic data to design a plant-tissue-based antibody (immunoglobulin) for the treatment of cancer. For this purpose, the binding specificity of the antibody to its target was calculated from a bioinformatics-based data set (genomic and proteomic data). The designed gene sequence for the antibody was then introduced into tobacco cell culture in fermenters, where the protein (i.e. the antibody) was expressed (for further details, see Ma et al. 2005). This knowledge has recently been accelerated by the use of AI (Fig. 5.8).

Biotechnologies, as defined above under 'green biotechnology' also make use of biological principles and processes. A distinction is made between conventional and molecular biotechnology. Conventional biotechnology uses microorganisms, for example, in food production processes such as fermentation, often with enzymes catalysing the reactions. Molecular biotechnology uses laboratory techniques to study and modify nucleic acids and proteins. Genetic engineering makes use of techniques from molecular biotechnology. The application of biotechnology can be supported by omics, as described above in the example of using bio-based genomic data for the design of a plant-tissue-based antibody (immunoglobulin) for the treatment of cancer.

Biological knowledge also includes the understanding of naturally occurring mechanisms, known as bionics. Bionics is a branch of science concerned with the analysis and characterization of materials, organizational structures, processes and principles of living nature, and the transfer of the knowledge gained in this process to technical applications. The term 'bionics' is derived from 'biology' and 'technics'. 'Biomimetics' is often

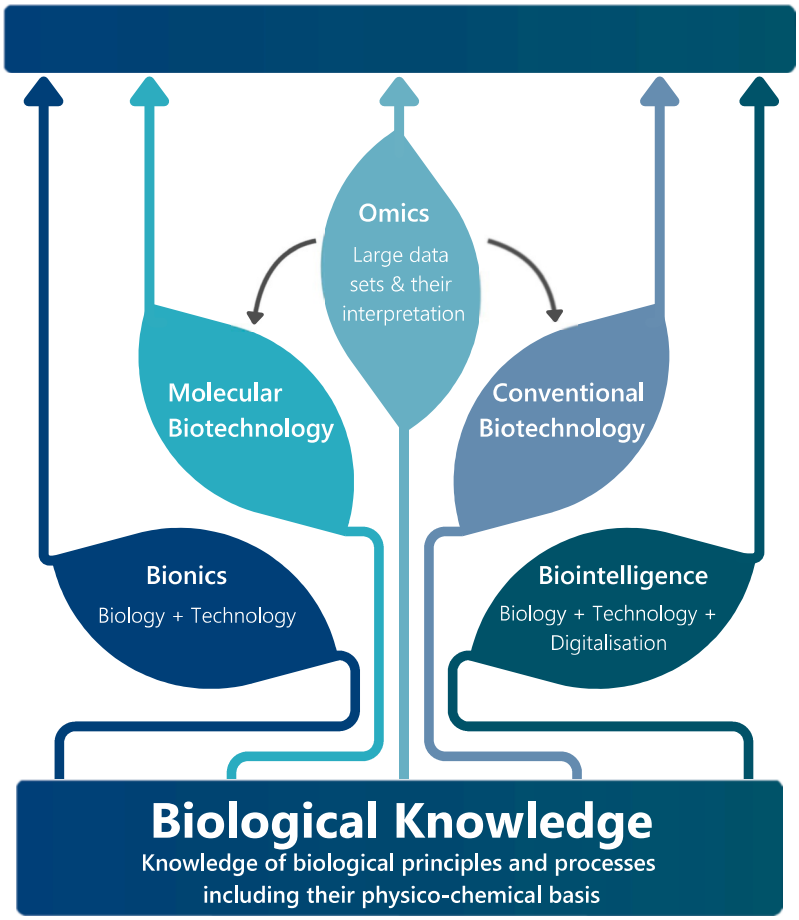


Fig. 5.8 Description and elements of biological knowledge, including 'omics' for learning from large data sets, conventional and molecular biotechnologies, and bionic and biointelligence approaches

used as a synonym for bionics. The most important feature of bionics is that it does not involve the direct transfer of biological phenomena to technology, but rather identifies the principle behind the respective biological phenomenon, the understanding of which is then implemented in a new invention at the level of technology (see Fig. 5.9).

Do you want to learn more about biomimetic/bionic approach? Take a look at Supplementary Video 5.1, a video from our MOOC "Concepts of Sustainable Bioeconomy" (2021).

One prominent example is the so-called 'lotus effect'. It describes the self-cleaning properties of the lotus plant (*Nelumbo nucifera*) resulting from the ultra-hydrophobicity of the wax layer on the surface of its leaves. Technical application of this mechanism is used in paints, coatings, roof tiles, fabrics and other surfaces that can stay dry and clean themselves. *Biologization* is the integration of such natural concepts into economic development, the application of biological and life science innovations and the development of products and solutions through life sciences. Biologization and digitalization (as seen in the example of bioinformatics above) are often considered as convergent and potentially synergetic processes.

Biologization and digitalization together form the basis of the emerging concept of biointelligence. There is no general definition

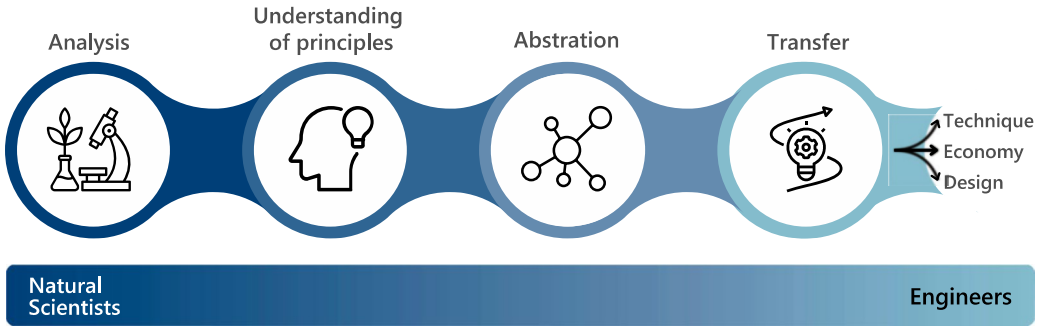


Fig. 5.9 The biomimetic/bionic approach. (Based on Schwarz 2021)

of biointelligence, but it can be described as "linking biological and technical systems via information and communication technology (ICT), enabling regional, small-scale, recyclable, resilient, demand-oriented, and highly automated production technologies and value-added chains, which in turn will allow the purposeful management of biological resources in the form of a technology-oriented demand economy" (Miehe 2024, p.4).

5.5 Nature-Based Solutions

According to the International Union for Conservation of Nature and Natural Resources (IUCN), 'Nature-based Solutions (NbS) are actions to **address societal challenges** through the protection, sustainable management and restoration of ecosystems, benefiting both biodiversity and human well-being' (International Union for Conservation of Nature and Natural Resources 2020).

The IUCN has also proposed a framework for NbS. They suggest grouping approaches that fall under the concept of NbS into five categories:

- Restorative (ecological restoration, forest landscape restoration and ecological engineering)
- Issue-specific (ecosystem-based adaptation, ecosystem-based mitigation, ecosystem-based disaster risk reduction and climate adaptation services)
- Infrastructure (natural infrastructure and green infrastructure)
- Management (integrated coastal zone management, integrated water resources management)
- Protection (area-based conservation approaches, including protected area management and other effective area-based conservation measures) (Cohen-Shacham et al. 2019).

In 2022, the United Nations Environment Assembly defined NbS as 'actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human wellbeing, ecosystem services and resilience and biodiversity benefits' (UNEA 2022, UNEP/EA.5/Res.5 paragraph 1). In the UNEA definition, NbS interventions are divided into four categories: Protect, Restore, Conserve, Manage.

Another definition of NbS is given by the EU: 'Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions'. "Nature-based solutions present a credible means to address key societal issues, such as biodiversity loss, climate change, and disaster risk reduction." (European Commission 2022).

The nature-based solutions Initiative states that 'Nature-based solutions involve

working with nature, as part of nature, to address societal challenges, supporting human well-being and biodiversity locally. They include the protection, restoration or management of natural and semi-natural ecosystems; the sustainable management of aquatic systems and working lands; and integration of nature in and around our cities. They are actions that are underpinned by biodiversity and designed and implemented in a way that respects the rights, values and knowledge's of local communities and Indigenous Peoples'. (Nature-based Solutions Initiative 2024).

Practical examples of nature-based solutions include:

- **Urban green spaces**: Creating parks, green roofs, green walls and community gardens in urban areas to enhance biodiversity, reduce urban heat islands, improve air quality, and provide recreational spaces for residents (see ▶ Sect. 7.2).
- **Wetland and drained peatland restoration**: Restoring wetlands to increase flood control, improve water quality, provide habitat for wildlife and promote carbon sequestration.
- **Mangrove restoration**: Rehabilitating mangrove forests to protect coastal areas from storm surges and erosion, sequester carbon, enhance fishery productivity and provide habitat for birds.
- **Agroforestry**: Integrating trees and shrubs into agricultural landscapes to improve soil health, increase crop yields, enhance biodiversity, and provide additional sources of income for farmers (see ▶ Sect. 7.1).
- **Afforestation and reforestation**: Planting of new forests on land that has not been forested for a period of at least 50 years, that is, afforestation, and reforestation of land previously forested but that has been converted to non-forested land, for the purpose of carbon sequestration in biomass and soil (see ▶ Sect. 8.5.4).

A study by Mauchaza et al. (2024) examined the extent to which Nature-based Solutions promote transformative change for the sustainable use and management of biodiversity in socio-ecological systems worldwide. The globally selected case studies were assessed against three types of NbS outcomes: *biodiversity and environment*, *quality of life* and *nature's contribution to people*. It was found that in all case studies, NbS was mainly used to address environmental degradation through the application of NbS interventions classified as *manage* and *restore*. Other NbS interventions fall into the category *restructuring*. Here, the restoration of a river or forest entails environmental restructuring or the creation of new marine management areas. Overall, *biodiversity and environment* was the most frequently reported outcome.

5.6 Primary Production

Primary production is the synthesis of organic substances by autotrophic organisms from atmospheric or aqueous carbon dioxide (CO_2) (see ▶ Sect. 5.1). Primary productivity, which is the rate at which energy is converted into organic substances, depends on internal (genetic) and external (eco-physiological) factors. ◘ Figure 5.10 shows that the net primary production of biomass is highest in regions where high temperatures are combined with a good water supply and is totally absent in desert regions without a natural water supply.

Apart from light and water, there are other factors that determine primary productivity, including the availability of plant nutrients, mainly nitrogen (N), potassium (K) and phosphorus (P) (see ◘ Fig. 5.3). The lack of any one of these factors can hinder biomass growth. Unfavourable site conditions, such as soil contamination or compaction, can also impair biomass growth conditions. Because the process of photosynthesis consumes CO_2, potential biomass productivity increases with increasing atmospheric CO_2 concentrations. However, this additional stimulus cannot be transformed into higher productivity if water supply is limited by drought. That means the highest biomass growth is achieved when all factors affecting growth are at their relative optimum.

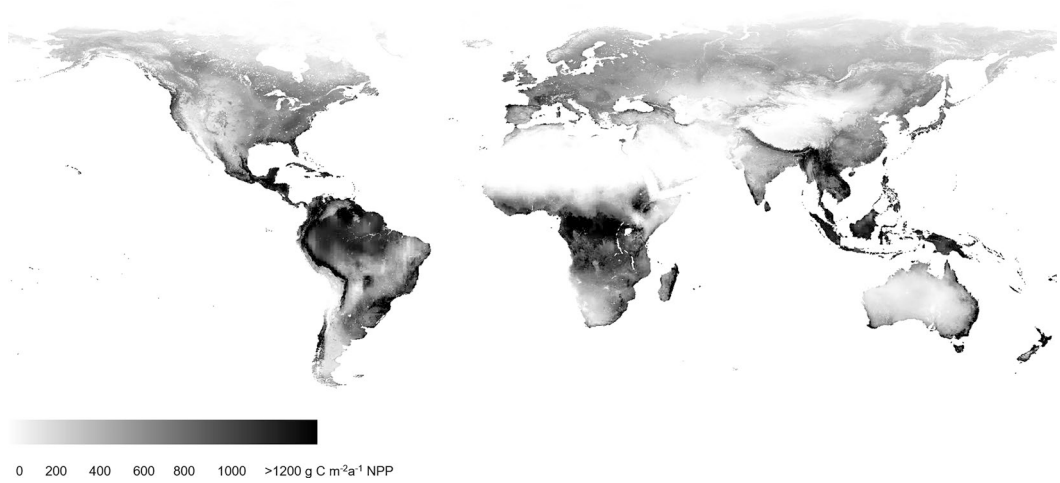


Fig. 5.10 Net primary production (NPP) of biomass, in gram increments of carbon (C) per m^2 and year. (Based on Imhoff et al. 2004)

Primary productivity also differs depending on the type of plant or organism and its genetics. An example of this can be seen in the productivity of 'C3' and 'C4' plants. Most crops cultivated in temperate climates possess the C3 photosynthetic mechanism, so-called because the first product of carbon fixation contains three carbon atoms. Wheat, sugar beet and trees are examples for C3 crops. Carbon fixation in the photosynthesis pathway of C4 crops results in a first product containing four carbon atoms. Sugar cane and other subtropical and tropical crops belong to this group. Under favourable environmental conditions, especially high temperatures, C4 crops are more productive than C3 crops because they possess a more effective biochemical mechanism of fixing CO_2. The genetic component of productivity can be exemplified by the breeding progress achieved in recent decades. It is presumed that the major proportion of yield increases seen in the agricultural crops wheat, rice and maize are the result of intensive breeding. Improved crop management, especially fertilization and crop protection, is the second most important factor driving yield increases.

Biomass is produced on a land area of 14,900 million ha (Mha) globally, of which 1500 Mha are arable land, 4100 Mha are permanent grassland and pastures, and 3900 Mha are forest (see Fig. 5.11).

Actual biomass production very much depends on the kind of land use. The highest productivity is generally achieved on intensively managed cropland with natural vegetation generally having the lowest.

It is anticipated that a growing bioeconomy will require an increasing supply of biomass. However, not all of the biomass produced can be made available for use. For example, in the context of bioenergy development, there is an ongoing debate about biomass availability and whether the energetic and material use of biomass is in conflict with food supply.

The question of how much biomass can be sustainably used for human consumption, especially for bioenergy, has led to various biomass potential analyses being performed. Several global biomass potential assessments indicated that an additional biomass potential exists for material or energetic application that could be used without jeopardizing food supply (Dornburg et al. 2010; Smeets et al. 2007). The methods applied in these studies are generally supply-driven, which means they assess biomass potentials on the basis of resources available for biomass production. These resources are either additional land or land that can be more efficiently used to increase biomass productivity. Other supply-driven studies assess and quantify potential biomass supply from

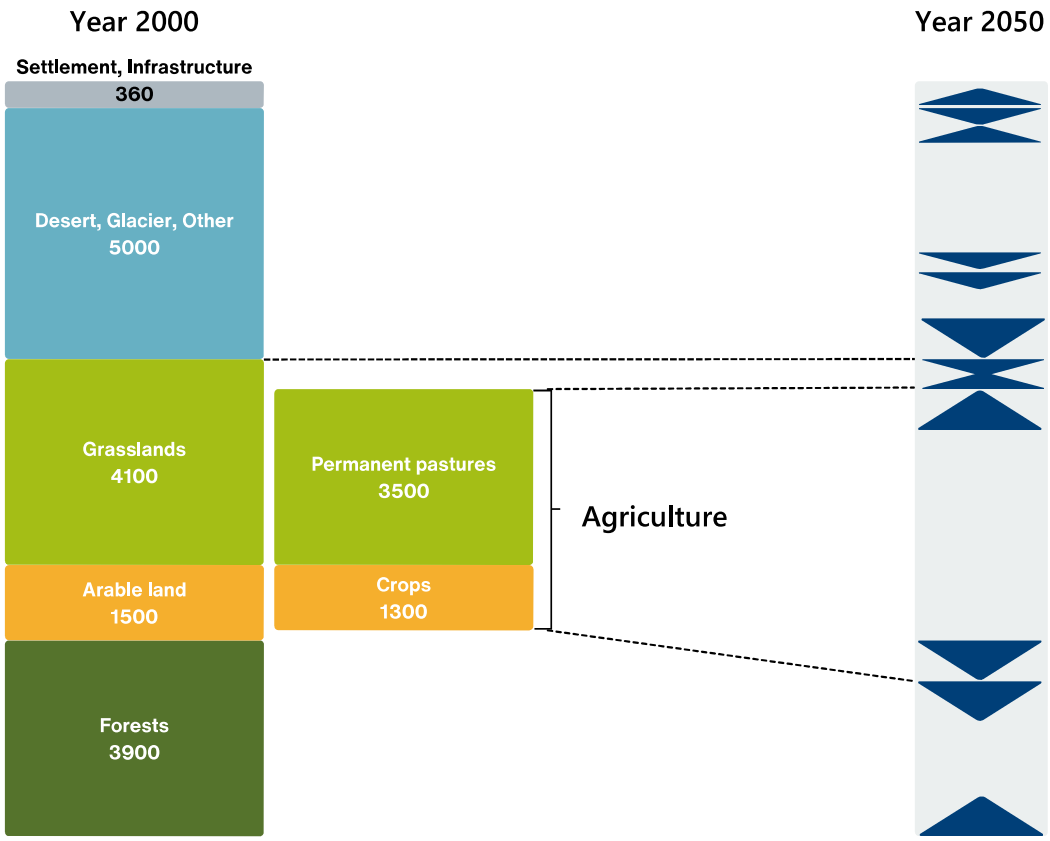


Fig. 5.11 Major types of global land use cover in Mha and future trends. (From Bringezu et al. 2014). Built-up land (i.e. land used for settlements and infrastructure) expands mostly at the expense of agricultural land, while agricultural land expands mostly at the expense of forest area

untapped or underutilized resources, such as agricultural and forestry residues, landscape and grassland biomass, and other organic waste.

Today, it is generally agreed upon that biomass potential assessment studies should follow the following rules (see also Dornburg et al. 2010):

- They should only consider biomass that is not required now or in future for the purpose of food production. A biomass potential should only be indicated as such if it can be generated in addition to products from primary production needed for food or feed purposes.
- Biomass should not be produced in any areas of high conservation value (HCV). By the High Conservation Value Resource Network (HCVRN) Common Guidance for Identification of HCVs it is defined that "An HCV is a biological, ecological, social or cultural value of outstanding significance or critical importance". The six HCVs categories include i) Species diversity, ii) Landscape-level ecosystems, ecosystem mosaics and intact forest landscapes, iii) Ecosystems and habitats, iv) Ecosystem services, v) Community needs and vi) cultural values (Brown et al. 2013).
- Biomass should not be produced where it would lead to the destruction of high-carbon land-use systems, such as peat, natural forest or permanent grasslands.
- Biomass should be generated from the more efficient use of existing agricultural land and sustainable extraction from natural forests or other land-use forms. In addition, more efficient use should be made of existing biomass resources, for

example, through more efficient biomass conversion techniques, and of residue streams to increase the biomass potential.

Several studies have resulted in global biomass potentials ranging from 0 to more than 1100 GJ (Dornburg et al. 2010). The background assumptions applied in the modelling approach form the major determinant of the size of the biomass potential given. There are many factors that determine the sustainably usable biomass potential (Smeets et al. 2007; Dornburg et al. 2010) including:

- The local diet, mainly the kind and amount of meat and dairy products consumed. The biomass potential decreases with an increase in the amount of meat consumed because meat production requires 3 to 100 times more land than crop production (Smeets et al. 2007).
- The type and efficiency of meat production. The efficiency of meat production, expressed in terms of kg of meat produced per kg of feed, differs between animals, regions, feeding systems and others (see ▶ Sect. 6.10, ◘ Table 6.5).
- The efficiency of agricultural land use. The actual exploitation of agricultural land, indicated by the proportion of potential yield that is actually harvested, varies widely between countries. It can be close to full exploitation in industrial countries but as low as 30% in some African countries. Because biomass potentials are generally assessed by multiplying the respective yield by the amount of land available, the yield assumed is also a major determinant of biomass potentials.
- The amount and quality of land considered available for biomass production. The amount of land that is additionally available for biomass production is currently a topic of ongoing debate, especially on the background of increasing demand for food production. Therefore, so-called "marginal land". Has come into focus as potential for additional biomass production. Marginal production conditions can be defined in economic and bio-physical terms (Dauber et al. 2012), but also in social and economic terms (Ahmadzai et al. 2022). Bio-physical constraints to agricultural production include, for example, degradation through erosion, contaminations, stoniness or shallow and low-fertile soils. If marginal land is defined as land that does not support economically viable agricultural production, the status of marginality will depend on land use and biomass prices. A caveat to the use of economically marginal land is the fact that the production of whatever biomasses, be it for food or energetic and material uses, on this land will result in low profit. Ahmadzai et al. (2022) estimate that there are about 1.4 billion ha of prime land (class very suitable in the GAEZ classifications) and good land (classes suitable and moderately suitable) that could be brought into cultivation if needed. However, this would come at the expense of pastures. Also, significant development investments, for example, for infrastructure, would be required.
- The kind of biomass being considered. Lignocellulosic crops, such as trees and grasses, deliver the highest biomass and energy yields per hectare. Many early potential studies (Hoogwijk et al. 2005; Smeets et al. 2007) are based on the assumption that short rotation coppice is grown on land available for biomass production. However, a number of material applications and liquid biofuel production require vegetable oils, sugar or starch. These can only be produced at lower yield levels.
- The share of residual biomass used. Residual biomass is produced during primary production and industrial processing of biomass. Depending on the crop and processing it can make up to 50% of the totally produced biomass, for example, in cereal production about 1 kg of straw is produced along with every kg of grain. As in the case of straw, residual biomass may at least partially be already used, for example, it is kept on the field for maintaining soil fertility or for animal bedding. But there is also a largely unknown amount of untapped resources of residual biomass that may be salvaged and valorised within bioeconomy solutions.

Agriculture and forestry are the largest primary production sectors, followed by fishery, aquaculture and the production of algae and microorganisms. Each of these primary sectors forms an important part of the bioeconomy. They are described in the following chapters.

Questions

1. What are the main resources used in the bioeconomy?
2. How can biological knowledge be applied?
3. Describe the energy balance of biomass production through the process of photosynthesis.
4. Which plant nutrients are important for biomass formation?
5. Which input and output traits are relevant for plant modification?
6. How can Nature-based Solutions (NbS) be applied in climate change mitigation?
7. What are the main factors determining the availability of biomass to energetic and material uses?

Answers

1. The bioeconomy uses bio-based resources derived from biomass that originates from plants, animals and microorganisms. Bio-based resources can stem directly from primary biomass or can be process residues or organic wastes recoveries. Another type of resource used in the bioeconomy is biological knowledge, which is the knowledge of biological principles and processes.
2. There are several approaches and technologies through which the knowledge of biological principles and processes can be applied. Biotechnology uses microorganisms in industrial processes to produce food, drinks or chemicals. Molecular biotechnology is applied to modify the characteristics of crops to make them more stress tolerant. Bionics uses biological knowledge to derive principles that can be used to design technical systems.
3. The energy balance of biomass production through the process of photosynthesis uses light as photons, CO2 and water to form organic molecules such as the monosaccharide glucose and energy in form of ATP. These resources can be used by the plant to produce starch, other carbohydrates, protein, fat or oil, or other secondary plant substances such as vitamins.
4. Plant nutrients are differentiated into macronutrients, required by the plant in large quantities, and micronutrients, required in smaller quantities. The most important plant nutrient that promotes mass growth is nitrogen (N). Other macronutrients essential for plant production are potassium (K), phosphorus (P) and calcium (Ca).
5. Input traits are those that affect crop performance without changing the nature of the harvested product and can e.g. induce resistance to pests and diseases. Output traits change the quality of the crop product itself, by altering starch, protein, vitamin or oil (omega-3 fatty acids) composition. Other output-trait-related targets include enhanced levels of essential minerals such as Fe and Zn, elimination of allergenic proteins, improved taste, longer shelf life and the introduction of novel food products.
6. Nature-based Solutions make use of natural processes to extract CO2 from the atmosphere and sequester it. CO2 is taken up from the atmosphere through the process of photosynthesis. The carbon is assimilated into the biomass, which can be incorporated into the soil where the carbon is sequestered in soil organic matter.
7. The amount of biomass that is available for energetic and material uses, mainly depends on the requirements to biomass for fulfilling food and feed purposes and on the efficiency of agricultural production. Animal production consumes most agricultural biomass. Therefore, significantly more biomass is available when people are relying on plant based diets.

A high productivity in agricultural production increases the amount of biomass produced per area unit and thus decreases the land-use demand. Lignocellulosic, non-edible biomass generally delivers higher biomass yields per area unit than the production of sugar, starch- or especially oil-rich edible biomasses. Lignocellulosic biomass can often be acquired from agricultural residues and its availability depends on the residue recovery rate.

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Agricultural Production

Iris Lewandowski, Melvin Lippe, Moritz von Cossel, Evelyn Reinmuth, and Joaquín Castro-Montoya



Fig. 6.0 Agricultural production. (© Ulrich Schmidt) (▶ https://doi.org/10.1007/000-htg)

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Agriculture is the cultivation of crops or the husbandry of livestock in pure or integrated crop/animal production systems for the main purpose of food production, but also for the provision of biomass for material and energetic use. Together with forestry, agricultural production represents the main activity of resource production and supply in the bioeconomy and is the major activity delivering food as well as starch, sugar and vegetable oil resources. Today, 33% (about 4900 Mha) of the Earth's land surface is used for agricultural production, providing a living for 2.5 billion people. Agriculture shapes cultural landscapes, but at the same time is associated with degradation of land and water resources, deterioration of related ecosystem goods and services, is made responsible for biodiversity losses, and accounts for about 12% of global greenhouse gas emissions. In this chapter, the principles of agricultural production, including crop management and animal raising, are described. The focus is on describing how in the future bioeconomy, agriculture can be performed sustainably. Sustainable intensification can partly be achieved by the development and implementation of innovative production technologies, which allow a more efficient use of natural resources, including land, and agricultural inputs. Its implementation requires a knowledge-based approach, in which farmers are made aware of the requirements of sustainable production and are trained in the implementation of sustainable agricultural production systems. The planning of bio-based value chains and sustainable bioeconomic development demands an understanding of the mechanisms of biomass production and supply (as described in this section) for the entire global agricultural sector.

Learning Objectives

After studying this chapter, you will…

- …be able to describe the determinants of agricultural productions systems and explain why different production and farming systems are adopted in different regions (see ► Sects. 6.1, 6.7, and 6.8).
- …be able to define an agroecosystem and explain how the climate and the physical and biological environments determine the options and performance of agricultural production (see ► Sects. 6.2, 6.3, 6.4, and 6.5).
- …be able to discuss the relevance of infrastructure and logistics for efficient agricultural production and explain how digitalization can support the production processes (see ► Sects. 6.6 and 6.11).
- …be able to describe the mechanisms and major management measures in crop production and explain why the appropriate crop and related management systems need to be chosen in a site- and context-specific approach (see ► Sect. 6.9).
- …be able to classify livestock production systems globally (see ► Sect. 6.10).
- …be able to explain the concept of feed conversion ratio (FCR) and discuss its relevance for efficient and sustainable livestock production (see ► Sect. 6.10).
- …be able to identify and explain the mechanisms and options for sustainable intensification of agriculture (see ► Sect. 6.11).
- …be able to identify the major impact factors for climate-smart farming (see ► Sect. 6.11).

Agriculture is the cultivation of crops and rearing of livestock in pure or integrated crop/livestock systems for the main purpose of food production, but also for the provision of biomass for material and energetic use. *Agricultural production systems* are determined by the following factors:

- the production activity (crop, animal or integrated crop/animal production);
- the organizational form (e.g. small-scale family or large-scale industrial farm);
- the climatic (e.g. tropical, temperate) and other environmental conditions (e.g. soil properties); and
- the socio-economic factors (e.g. population density, land availability, agrarian policy, farm and market structures).

Agricultural production is performed by farming entities, referred to in the following

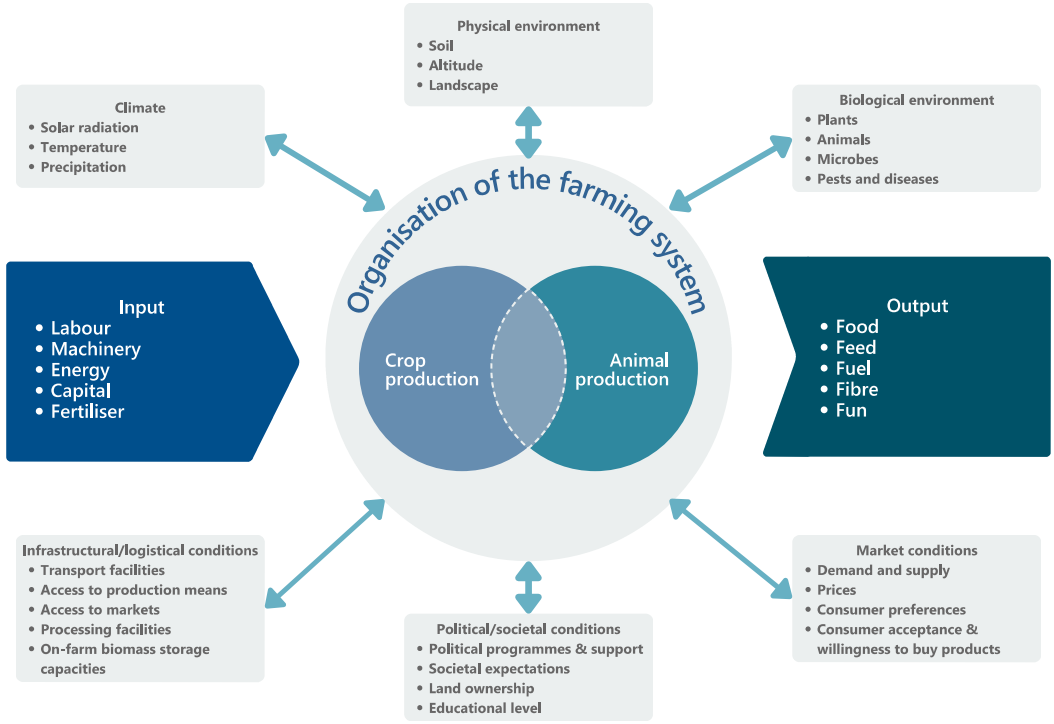


Fig. 6.1 Agricultural production systems and their determinants, here depicted as an overview of the multifaceted interrelationships of agricultural systems with society and the environment

text as 'farms' (▶ Sect. 6.1), on agricultural land (arable land and grassland) within agro-ecosystems (▶ Sect. 6.2).

This section describes how agricultural production systems are embedded in and determined by climatic, physical, environmental and societal conditions and the interactions (and interconnections) between them (Fig. 6.1). It also describes the principles of crop and animal production, their input and management requirements as well as their outputs, mainly in terms of yields and other ecosystem services.

6.1 Farm Types

Farms are the entities that perform agricultural production by either cultivating crops or rearing livestock, or by a mixture of both. Farms are in general characterized according to size, available resources, local options for crop and animal production, the organizational model and natural limitations of the surrounding agro-ecosystem, as a function of climate or soil types, and the interaction with other floral and faunal species (Ruthenberg 1980; Seré and Steinfeld 1996; Dixon et al. 2001).

Conservative approximations estimate that about 570 million farms currently exist globally, ranging from small-scale family farms to large-scale agro-industrially managed entities (Lowder et al. 2016). Family farms are still the most common farm type to date, where family members serve as the major work force of smallholding farms. About 84% of all farms worldwide are classified as small-scale family or smallholder farms, cultivating on average about 0.5–2 ha of land, with 72% cultivating less than 1 ha, and 12% cultivating about 1 to 2 ha only. These farms provide about 70–80% of agricultural products in Asia and Sub-Saharan Africa (IFAD 2013). Industrial farming is characterized by larger-scale farming types based on production approaches known from industry, that is, the use of mechanical-technical methods, great capital inputs and

high productivity. These farms can be organized as family farms as well as by company-based organizational structures.

Farming systems refer to the organizational form of agricultural production, including the farm as central operational entity and its interrelationships with the socio-economic, biological, physical, climatic and technical environment in a regional context (Fig. 6.1). A farming system is also characterized by the inputs for and outputs from agricultural production. Farming systems can be classified according to the following criteria (Dixon et al. 2001):

- Available natural resource base, including water, land, grazing areas and forest,
- Climate, with geographical co-ordination and altitude as important determinants,
- Landscape composition and topography,
- Farm size, tenure and organizational form,
- Dominant pattern of farm activities and household livelihoods, including field crops, livestock, trees, aquaculture, hunting and gathering, processing and off-farm activities,
- Type of technologies used, which determines the intensity of production and integration of crops, livestock and other activities,
- Type of crop rotation: number of annual, biennial or perennial crops grown in alternating sequence,
- Type of water supply: irrigated or rainfed,
- Share of annual and/or perennial crops used,
- Cropping pattern: integrated, mixed or separated cropping and animal husbandry,
- Degree of commercialization: subsistence, partly commercialized farming (if >50% of the value of produce is used for home consumption), and fully commercialized farming (if >50% of produce is used for sale).

Fallow is arable land left uncultivated (set to rest) for one or several years before being tilled again.

Ley systems are rotational farming practices that integrate grass or legumes with tilled crops (such as cereals) primarily as a soil conservation measure.

Annual crops and ***biennial crops*** are cultivated over a production cycle of one and two years, respectively. ***Perennial crops*** are cultivated over a production cycle of three or more years.

Note that fruit trees are often defined as perennial crops from an agricultural perspective and are not considered a forestry-based system. Exceptions here include 'agroforestry' types that combine trees with annual cropping or pasture systems.

Excursus 6.1: Agroforestry

Agroforestry is an integrated form of land use, "where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately integrated with agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence" (FAO 2024).

Agroforestry systems can productively integrate the ecological functions that perennial crops can provide into the agricultural systems. These functions include the creation of humus and carbon storage in soils, erosion protection, water retention in landscapes, the reduction of the entry of pollutants such as nitrate, pesticides into surface water and groundwater, habitat function and other ecosystem services. This is why agroforestry is an important agricultural practice in agroecological farming. The regional climate in the landscape and soil life can be improved, which can be particularly relevant for the management of less good agricultural land. The integrated land use system of agroforestry can increase area productivity and yield stability (Sesermann 2018) as well as carbon sequestration and humus formation (Aertsens et al. 2013).

In modern agroforestry systems, woody species are planted in multiple rows (alley cropping) on agricultural fields (see Fig. 6.2). Erosion is reduced when the tree rows follow the contour lines of slopes, while the deep roots of the trees reduce nutrient losses and eutrophication (Zhu et al. 2020). Additionally, the tree rows provide numerous habitat functions for fauna and flora (Hastings Silao et al. 2023).

Agroforestry is also considered a suitable climate change adaptation measure. The rows act as wind breaks and balance radiation, air and soil temperature, relative humidity and soil moisture of the agricultural fields. Microclimate regulation and balance makes agroforestry an important measure in times of increasing extreme weather events (drought, heavy rains, increasing temperature) due to climate change (Shukla et al. 2019; van Noordwijk et al. 2021). These potential benefits, however, vary with system design, e.g. in terms of type, management and distance of the tree rows and therefore the system design needs to be locally adapted.

All agroforestry systems deliver multiple products from the agricultural crops as well as the trees. Trees do not just deliver wood but also have the potential to deliver nuts or fruits. Figure 6.3 shows barley production in an agroforestry system in Germany and Fig. 6.4 an agroforestry system with olive trees in Southern Italy. These are only some examples of very diverse agroforestry systems that can be found in temperate as well as tropical regions. In all these agroforestry systems the trees deliver wood or edible products such as nuts.

Overall, agroforestry is a land use system that provides multiple ecosystem services to society (Cardinael et al. 2021) and multiple forms of biomass as food, feed, fibre and fuel for the growing bioeconomy.



Fig. 6.2 Agroforestry alley cropping trial with walnut trees, short rotation coppice and diverse hedges at the University of Hohenheim. (©Sandor Knecht)



Fig. 6.3 Barley in an agroforestry system at the University of Hohenheim. (© Moritz von Cossel)



Fig. 6.4 Agroforestry system with Olive trees in Puglia, South Italy. (© Iris Lewandowski)

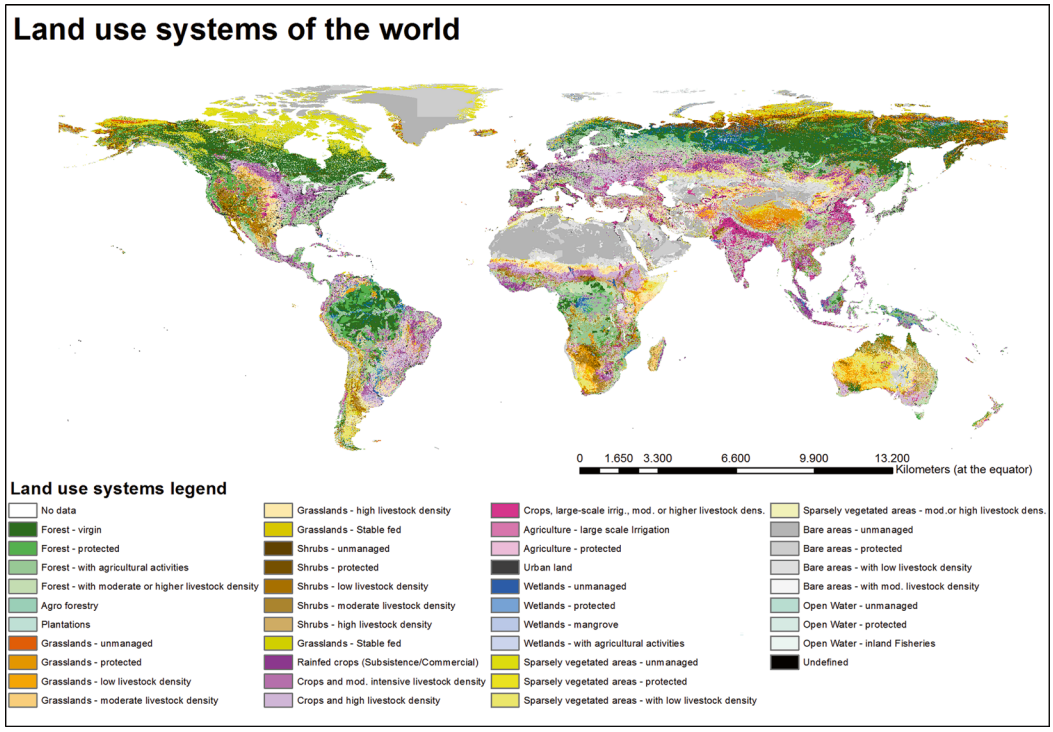


Fig. 6.5 Land use systems of the world. (Based on Nachtergaele and Petri 2008)

Figure 6.5 provides an overview of the global distribution of the most important farming and land use systems. Given the wide mix of farm systems possible locally, it distinguishes farm and land use types in broadly defined terms only.

Can you explain why the kind of farming systems that exist in your region have developed in the way they have?

6.2 Agroecosystems

An *agroecosystem* can be defined as the spatial and functional unit of agricultural activities, including the living (= biotic) and non-living (= abiotic) components involved in that unit as well as their interactions (Martin and Sauerborn 2013). It can also be described as the biological and eco-physiological environment in which agricultural production takes place. In this case, the environment consists of all factors affecting the living conditions of organisms. The different physical and chemical effects that originate from the non-living environments represent the *abiotic factors*. In terrestrial habitats, they essentially include the soil properties (e.g. pH value, texture, carbon content), specific geographic factors (e.g. topography and altitude), and climatic conditions (e.g. precipitation, light and thermal energy, water balance). The effects of *biotic* factors originate from organisms and can be exerted on other individuals of the same species (intraspecific), on individuals of a different species (interspecific), or on the abiotic environment (e.g. on specific soil properties). From the perspective of an individual species, the biotic environment essentially consists of other species, with which it has a relationship. These relationships can take different forms, including feeding relationships, competition and mutualism (Gliessman 2015; Martin and Sauerborn 2013).

6.3 Climate and Agricultural Production

As described above, the type of crops that can grow at a specific site mainly depends on the availability of water, the temperature and light intensity. Agricultural production can therefore be characterized according to climatic zone, classified as temperate, sub-tropical or tropical. Deserts also sustain some extensive agricultural through grazing. Climatic zones can also be distinguished according to the original vegetation, for example, forests. ◘ Table 6.1 gives an overview of the main climatic/vegetation zones, their characterization and selected major food and energy crops cultivated.

◘ **Table 6.1** Major agricultural production systems in different climatic zones of the world. (Based on: Davis et al. 2014)

Biome and type of agriculture	Rainfall mm a^{-1}	Temp. °C [*a]	Growing days[b]	Potential crops[c]
Subtropical/temperate humid forest Large commercial and smallholder: intensive mixed agriculture, cereals and livestock, tree crops	1000–2500	10–30	270–365	Cereals[d], fibres, oil crops, pulses, roots/tubers, coffee, tea, sugar crops, fruit, vegetables
Temperate broadleaved forest Large commercial and smallholder: tree crops, forest-based livestock, large-scale cereal and vegetables, cereal/livestock	250–1500	−10–30	90–365	Cereals[d], fibres, oil crops, pulses, roots/tubers, coffee, tea, fruit, vegetables
Temperate coniferous forest Forestry, large commercial and smallholder: cereals/roots, forest-based livestock	100–1500	−30–5	30–180	Cereals[d], roots, tubers
Temperate grassland Large commercial and smallholder: irrigated mixed agriculture, small-scale cereal/livestock, livestock	50–1000	−10–30	0–320	Cereals[d], fibres, oil crops, roots/tubers, sugar crops, fruit, vegetables
Tropical dry forest Large commercial and smallholder: tree crops, rice, cereals/roots	700–2500	15–30	30–300	Cereals[d], fibres, oil crops, tea, roots/tubers, coffee, sugar crops, fruit, vegetables
Tropical grassland Large commercial and smallholder: extensive, commercial ranching or mobile pastoralist systems, livestock	500–2500	15–30	30–300	Cereals[d], fibres, oil crops, tea, roots/tubers, coffee, sugar crops, fruit, vegetables
Tropical humid rainforest Large commercial and smallholder: subsistence agriculture, livestock, tree crops, root crops, partly protected land	1500–5000	25–30	300–365	Cereals[d], fibres, oil crops, pulses, roots/tubers, tea, coffee, sugar crops, fruit, vegetables
Temperate and tropical desert Pastoralism	0–350	10–40	0–30	Succulents

[a]Average annual temperature, based on FAO GeoNetwork (2017a, b)

[b]In general, growth is limited by rainfall (or water availability) in tropical climates and by temperature in temperate climates; species might have evolved locally in order to survive the extremes of climate, some crops may not, leading to zero growing days. Crop selection and management can potentially extend the growing season in other cases

[c]Within a biome, the suitability of a site for a particular crop depends on a range of factors, including altitude, rainfall and soil type. Crops listed here are examples and are not intended to be a comprehensive list

[d]Cereal crops are generally of the gramineous family and are cultivated to harvest dry grain only (as food or feed) or the total plants (as feed or bioenergy source), e.g. wheat, rice, barley, maize, rye, oat, millet, sorghum, buckwheat, quinoa, fonio, triticale and canary seed

6.4 Physical Environment and Agricultural Production

The physical environment determines options for agricultural production mainly through the topography of the landscape and soil properties.

The topography defines if or how well the land can be accessed and managed mechanically. Soil cultivation, such as ploughing, is difficult on steep slopes and there is the danger of erosion.

The soil characteristics most relevant for crop production are:

- Organic matter, which mainly occurs in the upper A soil horizon (see Fig. 6.6). Organic matter determines the soil's water-holding capacity and can supply plant nutrients.
- Soil texture or grain size distribution (clay: <0.002 mm; silt: 0.002–0.05 mm; sand: 0.05–2 mm), which determines the water-holding capacity and workability of the soil as well as its susceptibility to degradation processes.
- Soil reactivity, expressed using the pH value, which is a numeric scale used to specify the ▶ acidity (pH < 7) or ▶ basicity (pH > 7) of the soil.
- Soil depth, bulk density and stoniness. These determine the water-holding capacity of the soil, how well it can be treated mechanically, how well plant roots can penetrate it and how much space is available to plant roots for the acquisition of water and nutrients.

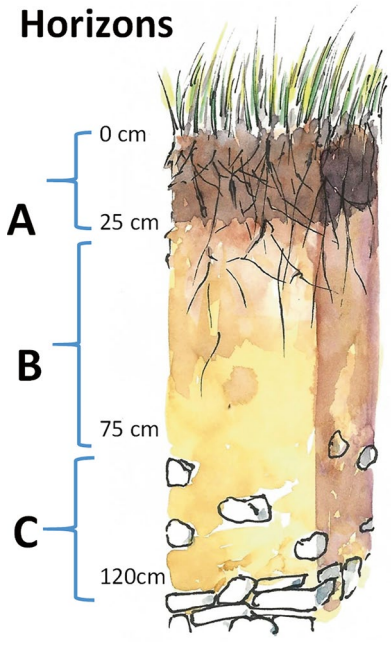


Fig. 6.6 Typical soil profile with different horizons

Crop production requires the natural resource soil. However, it is also directly or indirectly responsible for the largest part of soil degradation processes, such as erosion and compaction. Soil degradation can be caused by erosion through heavy rain (water runoff) or wind when the soil is not covered by crops. For example, when a forest is cleared to make room for agriculture, or if land is converted to intensive soil cultivation without applying appropriate counter measures such as integrating cover crops in the crop rotation or site-specific soil conservation management (avoiding soil compaction).

Degradation of agricultural soils can be prevented or even reversed by appropriate management methods, but in some cases, it requires time spans of decades or centuries for full restoration. Conservation and low-tillage farming, where the tilling of soil is kept to a minimum or avoided altogether, strive to preserve soil fertility. There are a range of measures through which the farmer can maintain soil fertility, including: (a) maximizing soil coverage by intercropping, crop rotation optimization and mulching; (b) enhancing soil organic matter supply through intercropping and applying crop residues; (c) reducing soil cultivation intensity and growing perennial crops; (d) avoiding erosion by contour farming, that is, soil cultivation parallel to slopes.

Soil erosion is the physical loss of soil caused by water and wind. Rainfall leads to surface runoff, especially when soil has been cultivated, is not covered by vegetation or is on a steep slope. Wind erosion mainly occurs in semi-arid and arid regions. In this process, wind picks up solid particles and carries them away. Erosion is a major process in soil degradation.

Soil compaction occurs when an impact or load on the soil presses the soil particles together, leading to a decline in pore size and total pore volume. The soil has a greater bulk density which leads to reduced water infiltration and drainage and slower gas exchange. Plant roots have greater difficulty penetrating the soil and accessing water and nutrients. Soil compaction can occur in agricultural production through mechanical soil cultivation or by heavy machinery being driven over the soil, especially when it is wet.

6.5 Biological Environment and Agricultural Production

The biological environment (= biotic factors) refers to the natural occurrence of organisms, including animals, plants, micro-organisms, bacteria and viruses, at a specific site. These can all become constraints to crop production and livestock husbandry, for example, through animals eating the crops, weeds competing with crops for nutrients and water, crops becoming infected with fungal, viral or bacterial diseases or the competition for or lack of fodder of moderate to high quality for animal feeding.

At the same time, agricultural production has a strong impact on biodiversity through the use of pesticides, herbicides and fertilizers, increased landscape homogeneity associated with regional and farm-level specialization, and habitat loss when natural vegetation is converted to agricultural land (Hilger and Lewandowski 2015; Lambin et al. 2001).

Mixed cropping systems can lead to higher overall product yields than monocultures. However, if the target is the maximization of the yield of one specific crop, the highest area yield is achieved by monoculture, that is, the cultivation of a single crop or variety in a field at a time. This is because the management system (crop protection, fertilization, harvesting time etc.) can be best optimized for a homogenous plant community. Any other plants in the field compete with the crop for growth-promoting factors (water, light and nutrients) and are therefore considered weeds that need to be controlled or eradicated in order to avoid a reduction in crop yield. Animals that feed on the crops are also in conflict with agricultural production, except for natural predators of pests (e.g. birds of prey that catch mice) and beneficial insects (e.g. ladybirds that eat aphids), which help to increase agricultural crop productivity.

There are two concepts which are often discussed in the context of agriculture and maintenance of biodiversity: land sparing and sharing. *Sharing* refers to the attempt to integrate as much biodiversity as possible into the agricultural area, generally at the expense of productivity. *Sparing* aims to divide the land into areas used intensively for agriculture and others left natural and uncultivated. There is scientific evidence that the principle of sparing may be more successful in supporting biodiversity than that of sharing.

6.6 Infrastructure, Logistics and Digitalization

Mechanization has greatly enhanced land use and labour productivity. In modern agricultural production, all processes of soil cultivation, crop establishment, fertilization, crop protection and harvesting are performed mechanically by agricultural machinery specifically optimized for the respective crop and this makes modern agriculture capital-intensive. Securing a reliable and efficient supply chain with minimal losses requires infrastructure and logistics for the agricultural production system, and storage and transport

of the products to the markets. The better the infrastructure and logistic conditions, the lower the supply chain losses. These losses can be as high as 70% in areas where agricultural infrastructure is poorly developed. Lack of infrastructure (roads, storage facilities) is seen as a major barrier to increasing biomass supply in developing countries. Huge investments would be required to overcome these bottlenecks.

Digitalization is becoming increasingly relevant in contemporary agricultural infrastructure. Modern tractors are equipped with electronic devices, such as GPS (Global Positioning System). Precision farming, for example, makes use of GPS, electronic sensors and computer programs to control the application of agrochemicals in a spatially-specific manner with efficient use of resources.

6.7 Political and Societal Conditions

Agricultural, environmental and market policies have a significant impact on agricultural production in terms of what is produced and how. Examples of market policy impacts are described in ▶ Sect. 27.5. Many nations have agricultural policy programs and, in the EU, the so-called *Common Agricultural Policies (CAP)* determine agricultural policies. These primarily control subsidies provided to farmers and production volumes of certain agricultural commodities. In the 1990s, European agriculture produced more than the markets could absorb without adverse price effects. For this reason, farmers were obliged at that time to set 15% of their land aside and were compensated for doing so. Today however, this land is required for the production of energy and industrial crops and there is no longer any obligation to set land aside. Current CAP rules determine how agricultural subsidies are coupled with environmentally beneficial management measures under the so-called *Cross Compliance (CC)* and farmers are obliged to integrate *greening areas* to support biodiversity.

Societal expectations determine how agricultural and environmental policy programs are framed. For example, in Europe there is low acceptance of genetically modified organisms (GMO, see ▶ Sect. 5.3) and it is strictly forbidden to grow genetically modified crops.

As described above, the evolution of farming systems very much depends on social structures, especially how land access is granted and who owns how much land. The educational level of farmers determines not only the success or income of their farms, but also whether they are willing and have sufficient knowledge to manage their farm sustainably. Finally, the empowerment of farmers is an important prerequisite for the shaping of sustainable agriculture in the future.

6.8 Market Conditions

The most important animal-based products globally are pig, cattle and chicken meat and raw milk from cattle (◘ Fig. 6.7). Rice, wheat and maize are the most important crop-based commodities and are traded globally. ▶ Chapter 27 describes how supply and demand steer the markets of agricultural commodities and determine market prices.

There are local, regional and global markets. The demand of those markets that are accessible to farmers determines what and how much they produce. Consumer preferences and the consumer's willingness to buy certain products and pay a certain price are important market determinants. The willingness of consumers to pay a certain price is especially important for sustainably or 'better'-produced products. One of the main challenges in a bioeconomy is that ecologically more sound production is accompanied by higher production costs. For this reason, bio-based or sustainably produced products are often more expensive than conventional products. Markets for bio-based products can only develop if consumers are well informed and willing to make a conscious choice for the 'better' product.

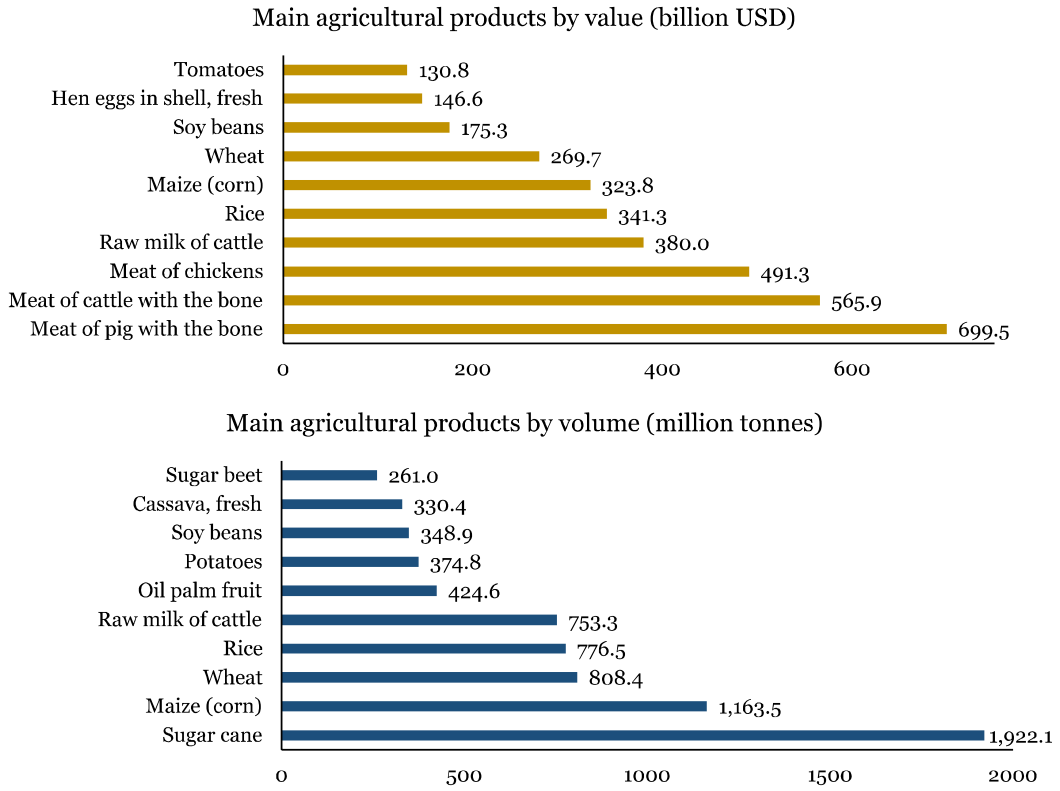


Fig. 6.7 Top agricultural products in terms of production value and production quantities—World 2022. (Data obtained from FAOSTAT (2022))

6.9 Principles of Crop Production

Every crop performs best in specific climatic conditions and can best be grown in either a temperate, sub-tropical or tropical climate (see also Table 6.1). The climatic profile of a crop is usually determined by the region of its origin (see Fig. 6.8 or Khoury et al. 2016a, b). Breeding can produce crop varieties that are adapted to specific climatic conditions. A prominent example is maize, whose cultivation area in Europe was extended north by breeding for cold tolerance.

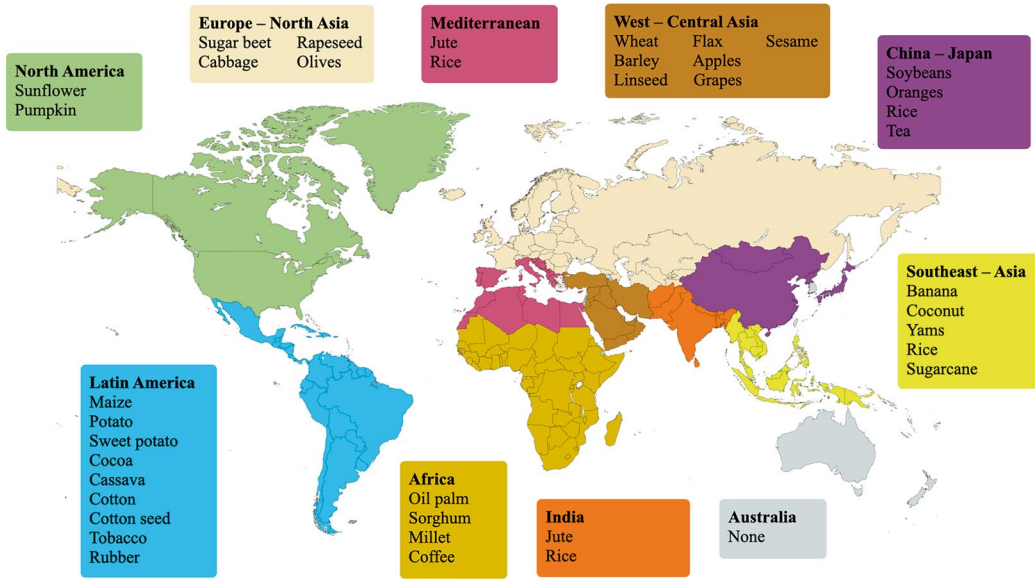


Fig. 6.8 Origin of important food and fibre crops. (Adapted from Khoury et al. (2016a), licensed under CC-BY 4.0)

6.9.1 Crop Management

The most important prerequisite for successful crop production is the choice of an appropriate crop and variety for a specific site. This does not only refer to climatic parameters. Crops also have specific demands with regard to soil conditions and biotic (e.g. pests and diseases) and abiotic (e.g. drought, contamination, salinity) stresses (see Fig. 6.9). In addition, the appropriate management measures, such as soil cultivation, need to be chosen according to the crop and site conditions (see Figs. 6.9 and 6.10). Whereas site conditions are given naturally, crop management is the anthropogenic influence on crop production.

Why is it not possible for all crops to grow everywhere?

Crop rotation is the temporal sequence of crops on a field. If annual crops (seeding and harvesting in the course of one year) are grown, the farmer can choose a new crop every year. Perennial crops are grown on the same field for 3 to 25 years or longer, depending on the optimal production period of the crop. Intercropping is the integration of a catch crop in between two major crops. Catch crops are often grown to reduce soil run-off (erosion) and nutrient leaching as well as to provide organic matter to the soil. Crop rotations are generally optimized from an economic viewpoint, that is, those crops with the highest market value are grown. However, there are biological and physical limits to crop rotation planning. It has to allow enough time for field preparation between the harvesting of one crop and the sowing of the next. Generally, it is not recommended to cultivate the same crop in a field for two or more consecutive years, as crop-specific pests, diseases and weeds can accumulate in the soil affecting the yield and quality of the subsequent crop. A change of crop is also necessary due to the depletion of soil nutrients. For this reason, it is recommended to avoid growing the same crop, or crops with similar demands and susceptibility to pests and diseases, in succession.

Soil cultivation is performed to loosen the soil, to incorporate residues, organic and mineral fertilizer, to control weeds and to prepare the soil for sowing or planting. The timing of and technology used for soil cultivation have to be adapted to the demands of the crop and soil conditions. Treating a wet soil and using heavy machinery can have negative impacts on the soil structure through compaction.



Fig. 6.9 Factors determining the success of crop production

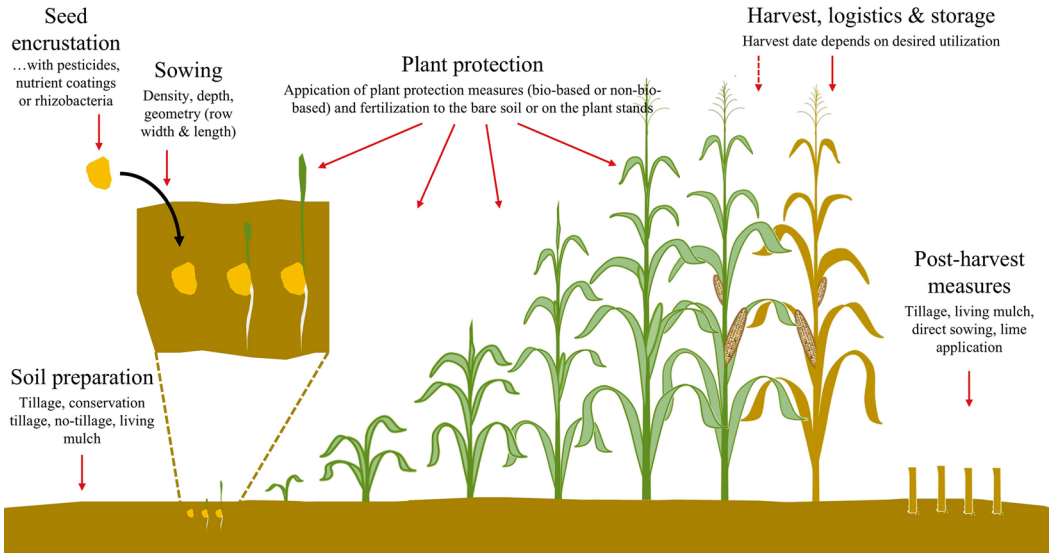


Fig. 6.10 Overview of agricultural measures and their chronological sequence (crop management) within the cultivation of the annual crop maize (*Zea mays* L). (© Moritz von Cossel)

Ploughing is the most effective soil treatment in terms of soil loosening and weed control (see Fig. 6.11). However, to protect soil organic matter and to reduce erosion, less intensive soil cultivation technologies are to be preferred. These, however, can lead to increased weed pressure and weed control demand.

Crops are established via *sowing* or *planting*. Sowing is cheaper and easier to mechanize, and is the method used for most major crops, such as cereals, maize, sugar, oilseed rape etc. Some crops have to be planted. Examples are sugar cane, which is established via stem cuttings, and oil palm, established via plantlets. In each case, the soil has to be prepared for planting by loosening it and removing weeds that would hamper crop establishment (soil cultivation).

Fertilization refers to all measures aimed at supplying nutrients to the crop (e.g. application of mineral or organic fertilizer) or improving soil conditions relevant for nutrient uptake (e.g. liming or application of organic substances). The optimal amount of fertilizer is determined according to the expected nutrient demand and withdrawal by the crop. Nitrogen (N) is the nutrient with the strongest yield effect. It is supplied to the soil via mineral or organic fertilizer, N-fixing legumes or atmospheric deposition. In organic agriculture, N is only supplied via organic fertilizer and biological N fixation (see Excursus 6.2). In addition, potassium (K), phosphorus (P) and calcium (Ca) are required for optimal crop growth and are generally applied when in shortage. As well as being a plant nutrient, Ca has an influence



Fig. 6.11 Intensive soil cultivation using a five-furrow plough. (© Moritz von Cossel). (▶ https://doi.org/10.1007/000-hth)

on soil structure and pH. The so-called crop *macro-nutrients* also include magnesium and sulfur (S). These are often combined with PK fertilizer and are only applied when there is an obvious shortage. This also applies to the so-called *micro-nutrients*, such as iron (Fe), chloride (Cl), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), cobalt (Co) and nickel (Ni), which are only required in small quantities. Typical fertilizer requirements of major crops, including biomass crops, of temperate regions are shown in Table 6.2.

In the bioeconomy, nutrients are recycled from organic waste streams or by-products—such as animal manure, crop residues, food scraps, and even human waste—into bio-based fertilizers or bio-based fertilizing products. Please refer to ▶ Chap. 14 for more information.

Crop protection refers to measures for the suppression or control of weeds, diseases, and pests as well as biostimulants that help to improve plant growth even under abiotic stress. Weeds compete with crops for all factors affecting growth and reduce crop yield and/or quality. So do pests and diseases, which feed on plant parts or their products of photosynthesis and often reduce the photosynthetically active surface area of plants. Every crop has a range of pests and diseases to which it is susceptible. Diseases can be caused by fungi, bacteria or viruses. If weeds, pests and diseases are not controlled, they can lead to large or total crop losses. Biostimulants can improve the natural resistance of plants through their growth-promoting effect (e.g. through improved nutrient absorption) and thus help to reduce the potential for disease infestation.

Excursus 6.2: Biological Nitrogen Fixation

Nitrogen (N) is one of the most abundant elements on Earth and occurs predominantly in the form of nitrogen gas (N_2) in the atmosphere. There is a specialized group of prokaryotes that can perform biological nitrogen fixation (BNF) using the enzyme nitrogenase to catalyze the conversion of atmospheric nitrogen (N_2) to ammonia (NH_3). Plants can readily use NH_3 as a source of N. These prokaryotes include aquatic organisms (such as cyanobacteria), free-living soil bacteria (such as *Azotobacter*), bacteria that form associa-

tive relationships with plants (such as *Azospirillum*) and, most importantly, bacteria (such as *Rhizobium* and *Bradyrhizobium*) that form symbioses with legumes and other plants (Postgate 1982).

In organic agriculture, BNF is the major N source and leguminous crops are grown for this purpose. There have been many attempts to associate N-fixing bacteria with crops other than legumes, with the objective of making them independent of external N supply. It is anticipated that BFN will play a major role in the sustainable intensification of agricultural production.

Table 6.2 List of selected crops with information on water, fertilizer and pesticide demand, parts harvested and constituents utilized

	Sugar cane	Maize	Soy	Oil palm	Miscanthus
Crop type	perennial	annual	annual	perennial	perennial
Photosynthetic pathway	C_4	C_4	C_3	C_3	C_4
Water demand (mm a^{-1})	high: 1500–2500	moderate: 670–800	moderate: 600	high: 2000–2500	low: >450
Fertilizer demand (kg ha^{-1} a^{-1})	N: 45–300 P: 15–50 K: on demand	N: 145–200 P: 26–110 K: 25–130	N: 0–70 P: 32–155 K: 30–320	N: 114 P: 14 K 159	N: 0–92 P: 0–13 K: 0–202
Pesticide needed?	yes	yes	yes	yes	no
Main parts harvested	stems, leaves	grain	grain	grain	stems
Constituents utilized	sugar	starch	oil	oil	lignocellulose
Uses	food, biochemicals/fuels, (feed)	food, feed, biochemicals/fuel	food, feed, biodiesel	food, biochemicals among others[a]	bioenergy, building materials, bio-composites, 2nd generation biochemicals, animal bedding

[a]Oil derivates are used in the cosmetic and other industries (from: Davis et al. 2014)

There are a number of crop protection measures including mechanical (e.g. weeding) and chemical (herbicides, pesticides) methods. In organic agriculture, no chemical-synthetical crop protection measures are allowed to minimize the impact on the environment. Instead, biological methods (e.g. natural predators, pheromone traps) are used together with bio-based pesticides (e.g. extracts from neem tree) and mechanical weed control.

Harvest technology and timing are relevant for the harvest index (proportion of harvested product versus residues) and the quality of the product. Appropriate harvest time and technology avoid pre- and post-harvest losses.

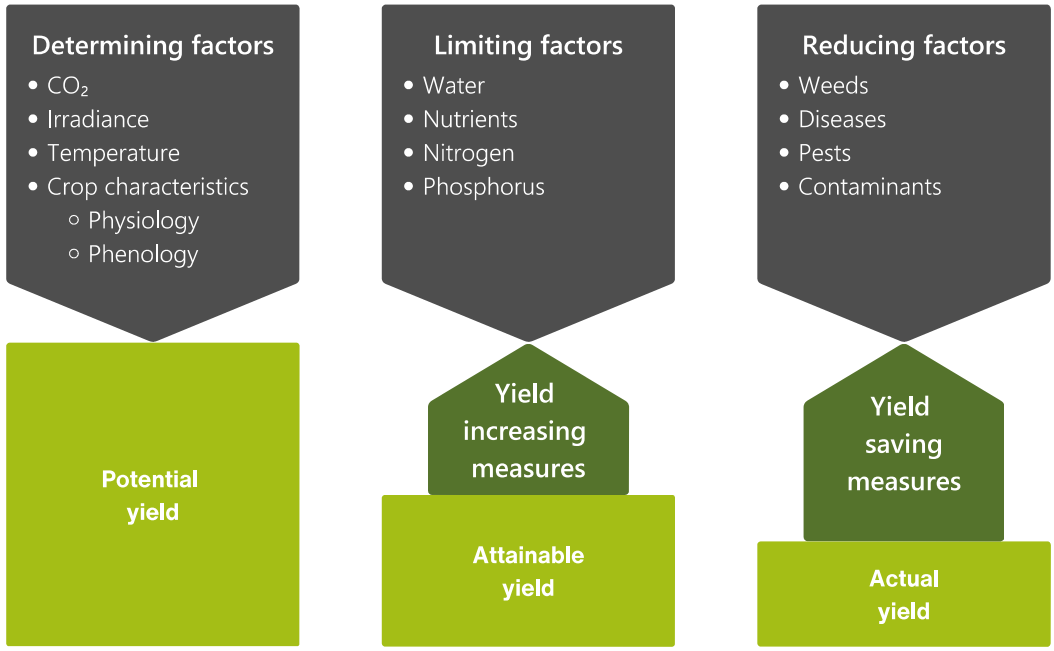
A ***Pesticide*** is 'any substance, or mixture of substances of chemical or biological ingredients, intended for repelling, destroying or controlling any pest, or regulating plant growth' (FAO and WHO 2014). Pesticides can have different chemical structures (organic, inorganic, synthetic, biological) and target organisms.

6.9.2 Crop Yields

Crop yields depend on the climatic and management factors depicted in ◘ Figs. 6.9 and 6.12. Thus, yield potentials have a climatic/site-specific and a management component. They usually increase with the educational level of farmers and their access to means of production, in particular modern varieties, fertilizer and pesticides. The potential yield on a specific site, which is mainly determined by crop genetics and growth-promoting factors, is generally much higher than the achievable yield (◘ Fig. 6.12). The achievable yield is limited by the availability of nutrients and water and can be improved by yield-increasing measures, such as fertilization and irrigation. The actually harvested yield, however, is normally lower than the achievable yield, because it is reduced by pests and diseases and/or harvest losses. These can partly be overcome through improved crop management and agricultural technology, such as efficient harvesting technology.

The ratio of actual to achievable yield is highest in industrial and lowest in developing countries where farmers have less access to means of agricultural production and are less educated. However, this does not mean that small farms that mainly use traditional farming methods cannot also achieve a high output per unit area (Altieri et al. 2012). For this reason, and also due to climatic differences, it is not possible to provide yield figures for the performance of a crop on every site and for all circumstances. ◘ Table 6.3 provides typical, average yields for selected major crops per hectare (ha = 10,000 m^2).

◘ Table 6.3 shows the yields of the main crop products. However, nearly all crops also deliver residual biomasses, such as the straw produced alongside cereal grain production (see ▶ Sect. 12.1.1). To estimate the yield of residual biomass, the so-called 'Residue-to-



◘ **Fig. 6.12** Determination of crop yields. (Adapted from Rabbinge 1993)

Table 6.3 Average yields of selected crops (in dry matter DM)

Crop	Harvested product (main ingredient)	Yields (t DM ha^{-1} a^{-1}) of harvested products			Typical uses	Major producing country
		low	average	high		
Temperate						
Wheat	Grain (Starch)				Food, Feed, Biofuel	Europe, Ukraine, USA
summer		3.4	5.4	7.1		
winter		5.4	7.4	9.5		
Corn/ Maize	Grain (Starch)	6.2	9.5	12	Food, Feed, Biofuel	USA, Europe
	Whole crop	12	18	25	Feed, Biogas	
Potato					Food, Feed, Biofuel, Bioplastics	Europe
Rape seed	Seed (Oil)	2.2	3.7	4.7	Food, Feed, Biofuel, Biochemicals	Europe
Sun flower	Seed (Oil)	1.3	2.5	4.3	Food, Feed, Biofuel, Biochemicals	USA,
Sugar beet	Beet (Sugar)	45	67	85	Food, Feed, Biofuel	Europe
Hemp	Fibre		0.77		Textile	China, Europe
Flax	Fibre		0.66		Textile	Europe, China
Subtropical						
Rice	Grain (Starch)				Food, Feed	Thailand, Vietnam, China, India
Corn/ Maize	Grain (Starch)				Food, Feed, Biofuel	USA, Europe
Sugar cane	Stems (Sugar)		71 (fresh)		Bioethanol, Food, Feed	Brazil, India, China
Soy bean	Grain (Protein, Oil)	2.9			Food, Feed, Biodiesel	USA, China, Brazil
Cotton	Fibre	2.0			Textile	Australia, India, USA
Tropical						
Cassava	Tuber (Starch)				Food, Feed	
Oil palm	Fruits (Oil)		2.9		Food, Cosmetics, Biochemicals, Biodiesel,	Indonesia, Malaysia, Nigeria
Abaca	Fibre		1.46		Yarn, ropes	Philippines, Abaca

From: KTBL (2015), FNR (2008), FAOSTAT (2014)

Product Ratio' (RPR) is applied. It estimates how much of a residual can usually be expected in relation to the main product. Different RPR values for the same product-residue pair can be found due to the reference condition of the biomass (dry vs. fresh matter), the crop variety, the production location and management system, as well as due to possible losses during harvest and different methodologies used to calculate the RPR.

6

6.10 Principles of Livestock Production

6.10.1 Global Livestock Population Trends

By 2018, the global market value of farmed animals ranged between 1.61 and 3.3 trillion USD, with cattle acounting for the largest proportion of both value and mass of farmed animals (Schrobback et al. 2023). Livestock has great significance in the livelihoods of people in the developing world, providing support for 600 million poor smallholder farmers (Thornton 2010). Between 1961 and 2022, the number of animals in the least developed countries (LDC) increased 2.98-, 7.77- and 7.52-fold for cattle, chicken and pigs, respectively, with major increases in the last two decades. By contrast, in the European Union (EU), livestock populations increased about 1.5-fold between 1961 and the beginning of the 1980s and since then, have remained more or less stagnant, with slight decreases in cattle and slight increases in chicken populations (author's own calculations; FAOSTAT 2017).

Primary production from livestock has increased in both developing and industrialized countries. In developing regions, this is a result of increasing livestock populations and performance levels (e.g. kg milk or meat/animal), whereas in industrialized countries the growth has almost exclusively been achieved by improving animal performance. There is still a large yield gap between industrialized and developing countries. In 1961, yields of chicken and pig meat per animal were 52% and 92% higher, respectively, in the EU than in the LDC. In 2014, these yields were still 40% and 49% higher, respectively, in the EU than in the LDC. For cattle, the productivity gap between industrialized and developing countries has even increased in the last 50 years. In 1961, milk yields were 9.8-fold higher and meat yields 1.5-fold higher in the EU than in the LDC. In 2014, they were 20- and 2.3-fold higher, respectively (author's own calculations; FAOSTAT 2017).

6.10.2 Classification of Livestock Production Systems

Livestock production systems vary greatly between different regions of the world and their development is determined by a combination of socio-economic and environmental factors. Many of these systems are thus the result of a long evolution process, and have traditionally been in sustainable equilibrium with their surrounding environments (Steinfeld et al. 2006). Livestock production systems are generally classified based on the following criteria (Seré and Steinfeld 1996; Steinfeld et al. 2006):

- Integration with crops
- Relation to land
- Agro-ecological zone
- Intensity of production
- Type of product

In this regard, most livestock production systems are classified into three categories:

- *Grazing-based systems*. In these livestock systems, more than 90% of feed dry mass stems from grassland. Of all the production systems, they cover the largest area: about 26% of the Earth's ice-free land surface (Steinfeld et al. 2006). This category mainly includes the keeping of ruminants in mobile or sedentary systems. Nomadic and transhumant systems have developed in regions of the world with high inter- or intra-annual variability in precipitation and/or ambient temperatures and thus plant biomass yields of grasslands. Examples include the steppes of Central and East Asia, the semi-arid to arid savannahs

of Africa, and the highlands of Europe, the Middle East, North Africa, and South America. Sedentary, grazing-based ruminant systems are normally found in regions with higher precipitation, lower climatic variability, and higher primary production of grasslands. These include, for instance, ranching systems of North and South America and Australia characterized by large pasture and herd sizes, as well as extensive, grazing-based cattle, sheep, and goat systems in Europe.

- *Mixed systems*. These are the most important production systems worldwide. They typically refer to mixed crop-animal systems, in which livestock by-products, such as manure and draught power, and crop residues are used as reciprocal inputs and where farmers commonly grow multipurpose crops (e.g. to produce grain for human consumption and stover for animal feed) (Thornton 2010). Two-thirds of the global human population live within these systems (Thornton 2010). Mixed systems are particularly relevant in developing regions, where they produce about three-quarters each of ruminant milk and meat, 50% of pork, and 35% of poultry meat (World Bank 2009).
- *Landless systems*. These systems represent livestock production units in which less than 10% of feed dry mass stems from the unit's own production (Seré and Steinfeld 1996). They are mainly pig and poultry systems. Globally, 55% of pig meat, 72% of poultry meat, and 61% of eggs are produced in these systems (authors' own calculations; Steinfeld et al. 2006). A minor proportion of beef cattle stocks that are raised in so-called feedlots also belongs to this category. Such landless systems are increasingly under pressure due to growing public awareness of environmental and animal welfare issues. In addition, (peri-) urban production units are commonly landless systems. Raising livestock within or in the vicinity of large human settlements provides fresh products to the markets, but also imposes health risks for humans due to the accumulation of animal wastes.

The livestock production systems described above are interrelated and very often modifications in one system will result in concomitant modifications in another. For example, landless milk production in Kenya depends on grazing-based systems for the replacement of the milking herd (Bebe et al. 2003). Therefore, the size and number of each type of production unit influences the other. Furthermore, human population growth and societal changes put each system under pressure to adjust to evolving market demands, growing urbanization, diminishing availability of traditionally used resources, and even increasing public scrutiny. Decreasing access to land and improving access to markets drive the conversion of extensive and mixed systems into more intensive production units, making these systems more efficient in the utilization of inputs to the livestock system. However, some of the systems will not be able to adapt to the new conditions, and will collapse (imploding systems) (Fig. 6.13).

6.10.3 Feed Resource Use in Livestock Production Systems

The *feed conversion ratio (FCR)* is a measure of the amount of feed (e.g. kg dry mass) needed by an animal to produce a unit (e.g. 1 kg) of meat, milk, or eggs. It is the inverse of feed conversion efficiency (i.e. the ratio between the product yield and the feed input). Hence, the lower the FCR, the more efficient the conversion of feed energy or nutrients into animal products. The FCR is higher if evaluated at herd level than at the level of an individual producing animal because the demand for feed biomass of non-producing animals in the herd is also taken into account. The FCR varies greatly between different livestock products, production systems, and regions of the world (Table 6.4). For instance, the FCRs for sheep and goat meat are more than nine times higher than for pig or poultry meat, and much higher than for milk. Furthermore, the FCR is higher in grazing-based than mixed and industrial ruminant livestock systems (Herrero et al. 2013), and higher in Sub-

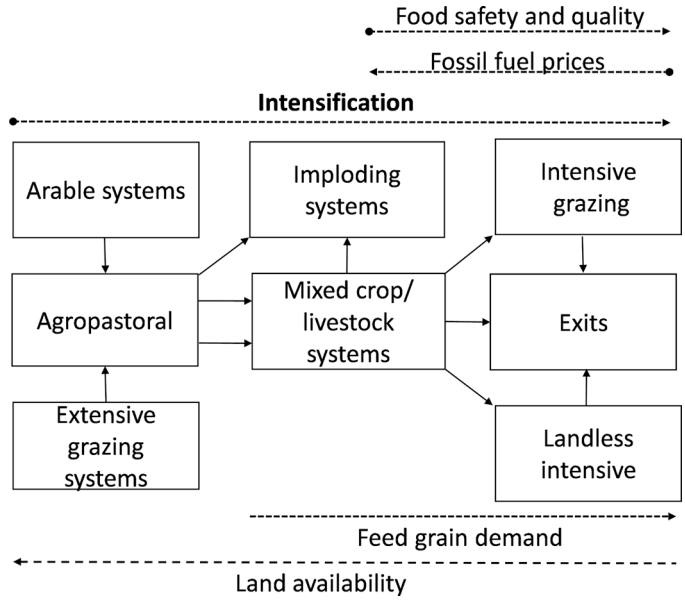


Fig. 6.13 Schematic presentation of development pathways of main livestock production systems and selected main drivers. (Adapted from World Bank 2009)

Table 6.4 Feed conversion ratio for the production of milk, meat, and eggs by different livestock species (in kg dry feed per kg animal product, evaluated for producing animals)

Region	Milk	Bovine meat	Sheep and goat meat	Pig meat	Poultry meat and eggs
North America	1.0	26	58	6.2	3.1
Oceania	1.2	36	106	6.2	3.1
Japan	1.3	15	221	6.2	3.1
West Europe	1.1	24	71	6.2	3.1
East Europe	1.2	19	86	7.0	3.9
C.I.S./Baltic States	1.5	21	69	7.4	3.9
Sub-Saharan Africa	3.7	99	108	6.6	4.1
Caribbean and Latin America	2.6	62	148	6.6	4.2
Middle East and North Africa	1.7	28	62	7.5	4.1
East Asia	2.4	62	66	6.9	3.6
South Asia	1.9	72	64	6.6	4.1

Modified from Smeets et al. (2007), based on Bouwman et al. (2005) and Bruinsma (2003)
C.I.S. Commonwealth of Independent States

Saharan Africa, the Caribbean, Latin America and South Asia than in North America and Europe.

This variation in FCR is mainly determined by the genetic potential of the animals and the intake, digestibility and nutrient concentrations of the available feed, with breeding and health management also playing a role. At low feed intake level, a major proportion of the energy (and nutrients) ingested by an animal is used for maintenance purposes or is lost via urine, faeces and the emission of methane, and only a minor proportion is converted into, for instance, milk or meat. However, with increasing feed intake, the proportion of feed energy (and nutrients) converted into meat, milk or eggs increases (Fig. 6.14; highlighted in green; van Soest 1994). Hence, improving energy and nutrient intakes and thus animal performance will greatly enhance the efficiency of feed resource use in livestock systems.

In line with this, the majority of monogastric (one stomach) livestock worldwide is kept in industrial systems, even in the less developed countries of South and East Asia, Latin America, and Sub-Saharan Africa (see above). Concentrate feeds (i.e. feeds rich in energy and/or protein and generally low in fibre, such as cereal grains and their by-products) as well as soybean and fish meal as high-quality protein sources commonly account for more than 80% of their diet (on a dry matter basis; Seré and Steinfeld 1996; Herrero et al. 2013). The high digestibility of these feeds promotes intake and animal growth rates. Consequently, the FCR in pig and poultry systems is much lower than in ruminant livestock (except dairy production) and are very similar across the various regions of the world.

By contrast, ruminant feeding is much more diverse, and their diets comprise (on a dry matter basis) at least 50% roughage (i.e. bulky feeds with generally higher fibre concentrations and lower digestibility than concentrate feeds) with a few exceptions, such as beef cattle finishing in feedlots. Moreover, the slower maturation and longer reproductive cycles of ruminants, as compared to pigs and poultry, result in higher proportions of non-producing animals within the herds. Consequently, the FCR at both the animal and system level is higher in ruminant than in monogastric livestock. The FCR in milk

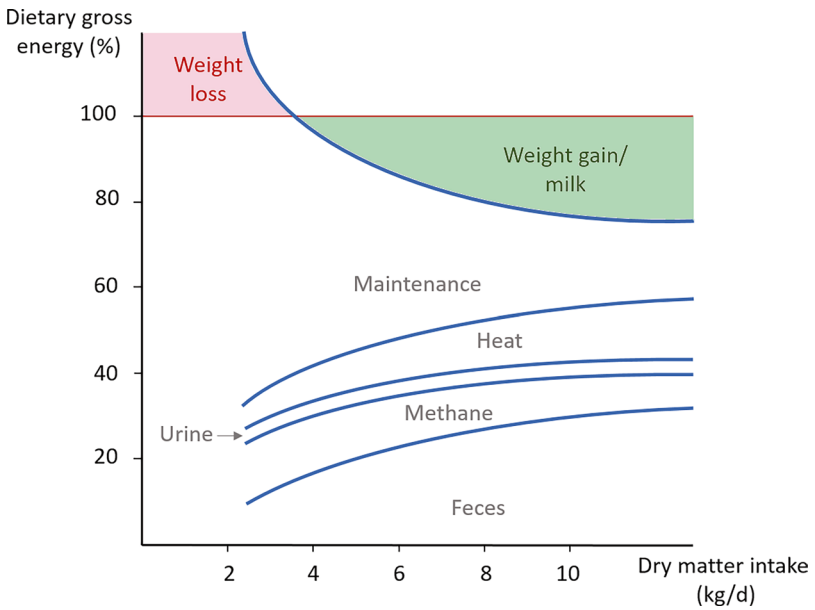


Fig. 6.14 Changes in the proportion of energy lost in faeces, urine, heat production and methane, and in the proportion of energy used for maintenance and weight gain/milk production with increasing feed intake in ruminants. (From van Soest 1994; based on Mitchell et al. 1932)

production is lowest. Because milk contains about 85% water, its nutrient and energy density is very low compared to other animal-derived food products. While most ruminant livestock in industrialized countries is kept in mixed systems (Seré and Steinfeld 1996) where feeding is based on cultivated forage and concentrate feeds, animals in other regions of the world commonly graze on (semi-)natural grasslands or are fed crop residues, and use of concentrate feeds is lower. These differences in diet composition and hence performance of animals are responsible for the differences in the FCR of ruminant products between the various production systems and regions of the world.

Excursus 6.3: Feed Conversion Ratio (FCR)

Common approaches to evaluating the FCR and ecological footprints of livestock systems do not differentiate between the types of plant biomass used as feed. For instance, the use of feed resources inedible for humans, such as roughage and crop residues, may reduce competition with plant biomass as food or feed. When expressed as the amount of energy and protein from human-edible feeds per unit of animal product, differences in FCR between livestock products become much smaller, because ruminant diets typically contain lower proportions of feeds suitable for human consumption. In some cases, the FCR is even lower for the production of beef than for pork, poultry meat and eggs (Wilkinson 2011). Similarly, these approaches only focus on either milk, meat or eggs as primary products and do not (adequately) account for other outputs or services provided by livestock. For instance, animal manure is an important source of nutrients for the maintenance of soil fertility in crop production, in particular in mixed farming systems of Sub-Saharan Africa, Latin America, and South and East Asia. Neglecting this additional output overestimates the actual FCR in mixed systems. Also, calves born in dairy cattle systems are also raised to produce meat. Correcting for the greenhouse gases emitted during the production of the same amount of meat in specialized beef cattle systems considerably reduces the carbon footprint of cow milk (Flysjö et al. 2012) and diminishes the differences between various production systems.

As the vast majority of expenses in livestock husbandry comes from the provision of animal feed, the FCR greatly determines the profitability of livestock farming. Moreover, the FCR is a key determinant of the demand for natural resources and the emissions of environmental pollutants in livestock systems. For instance, about 98% of the water needed to produce animal products (i.e. water footprint) is related to the production, processing, transport and storage of feed for livestock, whereas only 1% each is needed as drinking or service water (Mekonnen and Hoekstra 2010). Accordingly, the water footprints of beef, mutton and goat meat are higher than of pig and poultry meat; and are even higher in grazing-based than in mixed or industrial ruminant systems, in particular those of Europe and North America characterized by a lower FCR. There are similar differences in the carbon footprint of animal products (Herrero et al. 2013). Hence, any improvements in the FCR will greatly contribute to increasing profitability and reducing environmental emissions and (natural) resource use in livestock farming.

6.11 Towards Sustainable (Intensification of) Agriculture

6.11.1 Farming Concepts

In the bioeconomy, agriculture needs to be performed sustainably. This requires a definition and characterization of sustainable agriculture. One approach is to categorize farming systems according to their management concepts (see

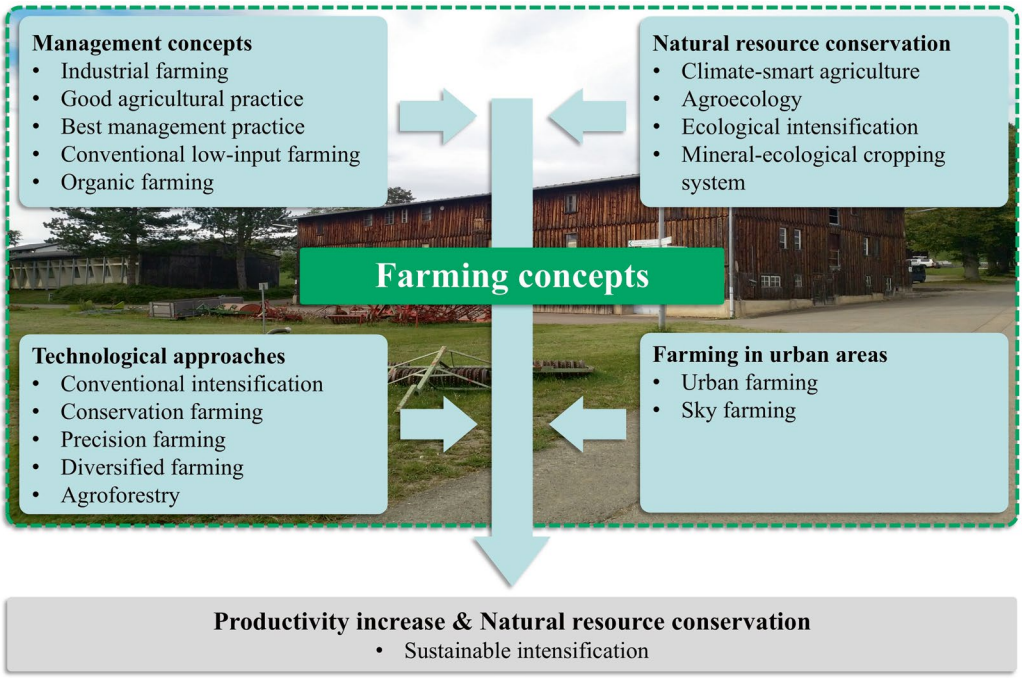


Fig. 6.15 Farming concepts are combinations of specific management and technology approaches (or concepts) aimed at increasing productivity and improved conservation of natural resources. (© Moritz von Cossel)

Fig. 6.15). Management concepts include clear regulations or concrete management measures for agricultural production. These are possible starting points for certification schemes. Certification ensures that producers follow certain rules during the production process. Certification schemes for agricultural products and foodstuffs provide assurance (through a certification mechanism) that certain characteristics or attributes of the product or its production method or system have been observed (see ▶ Sect. 31.2). Certification exists, among others, for organic agriculture (e.g. organic logo of the EU) or responsible farming practices (e.g. GLOBALG.A.P).

A number of farming concepts have been developed with a focus on natural resource conservation (Fig. 6.15). These include climate-smart farming, which aims to reduce greenhouse gas emissions from agricultural production and at the same time for less vulnerability to drought, pests, diseases and other climate-related risks and shocks.

With the objective of a more efficient agricultural production that has less impact on natural resources and also provides other ecosystem services (see Excursus 6.4 Ecosystem Services) than provisioning biomass, several technological approaches have been developed. These include, for example, conservation farming which has the conservation of natural resources, including soil fertility and genetic resources, in the focus. Another example is precision farming, which is the spatially specific and targeted management of agricultural land and fields, mostly supported through digital tools.

Excursus 6.4: Ecosystem Services

The diversity of factors influencing agricultural production (see Fig. 6.1) is reflected in the diversity of services provided by agricultural production. Since agricultural production processes are embedded in natural ecosystems, these services are referred to as ecosystem services and are divided into four main categories: provisioning services, regulating services,



Fig. 6.16 Examples of ecosystem services in farming systems and how to categorise them. (© Moritz von Cossel)

habitat services and cultural services (de Groot et al. 2012). In the literature, the exact designations and categorizations of ecosystem services sometimes differ, for example, regulating and habitat services are often summarised in one category, but the diversity of ecosystem services is usually clearly apparent (European Commission 2024).

The provision of biomass (e.g. in the form of fruits, wood, fibres, etc.) is just one of many ecosystem services that agricultural systems can provide (Fig. 6.16), but it is the most easily understood (quantity can be expressed in tonnes per hectare and harvest period) and the one that can be monetarised best (quantity multiplied by market price per unit of measure) of all ecosystem services (Von Cossel et al. 2020).

Thus, biomass supply can be planned, controlled and measured at the field level (Morizet-Davis et al. 2023). Other ecosystem services, especially in the category of regulating ecosystem services, usually extend beyond the field, up to the global scale (Morizet-Davis et al. 2023; de Groot et al. 2012). For example, the absorption of CO_2 and release of O_2 as part of the photosynthetic activity of plants means that agricultural systems make a significant contribution to air regulation (de Groot et al. 2012). It is therefore also an ecosystem service, but one that is more difficult to document and monetarise, although there are initial research approaches for doing that, albeit with numerous assumptions and limitations (Von Cossel et al. 2020; Kiefer et al. 2023).

There are major differences in the expression of these ecosystem services between land use systems depending on the crop type (annual or perennial) and the cultivation strategy (conventional or organic) of the land use systems. For example, the climate regulation of a wheat stand is less pronounced than in a primary forest, but it should not be omitted from an overall assessment of the ecosystem services of wheat cultivation. The same applies to the consideration of habitat services. These are less pronounced in a maize stand than in perennial wild plant mixtures, but they are not zero (Kiefer et al. 2023) and must therefore also be taken into account in a holistic assessment of the sustainability of maize cultivation.

While there are synergies between many ecosystem services in natural ecosystems or

traditional farming systems (e.g. higher genetic diversity -> better habitat services -> higher pollination services), industrial agricultural production also entails significant trade-offs, for example, between biomass and biodiversity protection (habitat services) (Kiefer et al. 2023). It is therefore not easy to optimise the performance of a cultivation system in terms of its overall ecosystem services, and it is always necessary to consider the current site-specific conditions (soil, climate, native flora and fauna, etc.) and the requirements of the farm (Morizet-Davis et al. 2023). To overcome these challenges, current research is investigating ways in which a meaningful holistic ecosystem service assessment of land use systems could be carried out (Wagner et al. 2022), for example, to enable continuous monitoring and adjustment during the vegetation phase (Morizet-Davis et al. 2023).

Farming in urban areas, also known as "urban farming" is discussed in the bioeconomy as an innovative approach towards the more regional food supply of the urban population, involving people as both consumers and potential producers of food (see ▶ Chap. 7). All these farming concepts apply management rules to define and operationalize sustainable agricultural management. In the following sections, a more detailed description of all these farming concepts is provided.

Do you want to learn more about multipurpose crops in the bioeconomy? Take a look at ◘ Supplementary Video 6.1, a video from our MOOC "Concepts of Sustainable Bioeconomy" (2021).

Management Concepts

Industrial farming, also denoted as *conventional farming* aims to maximize economic benefit through a high level of mechanization and the application of synthetic pesticides and fertilizers for crop production, and through the utilization of specialized breeds and intense feeding, health and reproductive management for animal production.

Conventional 'low-input' farming applying best management practices and integrated pest control, uses both synthetic and biological means of nutrient supply and pest control but applies input and management measures at levels considered economically justified and that reduce or minimize ecological and health risks. Additionally, integrated pest control makes use of naturally occurring strengths in plants and animals used for production purposes, like resistance to drought in certain crops, or tolerance to diseases and parasites in certain animal breeds. With this approach, this kind of farming seeks to optimize the management and inputs of agricultural production in a responsible way, through the holistic consideration of economic, ecological and social aspects. This approach aims at minimizing the input of agrochemicals and medicines to an economical optimum and includes ecologically sound management practices as much as possible. As one example, 'Integrated Pest Management (IPM) means the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human and animal health and/or the environment. IPM emphasizes the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms' (FAO and WHO 2014). Moreover, the close linkage of crop and livestock components in agro-ecosystems allows for efficient recycling of agricultural by-products or wastes, thereby reducing the reliance on external inputs such as fertilizers or animal feeds.

In *organic farming*, no synthetic fertilizers, chemical-synthetical pesticides or feed supplements are allowed. 'Organic Agriculture is a production system that sustains the health of soils, ecosystems and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic Agriculture combines tradition, innovation and science to benefit the shared environment

and promote fair relationships and a good quality of life for all involved' (IFOAM 2005). There are several variants of organic farming, including organic livestock production. All of them forbid the use of synthetic pesticides and fertilizers in crop production. Crop nutrient demands and crop health are managed through biological methods of nitrogen fixation, (see Excursus 6.2), crop rotation, biocontrol agents (living organisms), bio-based pesticides (see Fig. 6.17) and the application of organic fertilizer. The latter could be, for example, animal manure, digestate coming from biogas plants or organic fertilizers that were produced from agricultural residuals. Regarding livestock, organic production fosters the welfare of animals, and it restricts the use of synthetic feed supplements to those conditions where the welfare of the animal might be compromised by a serious deficiency. Similarly, organic livestock production focuses on disease prevention and it prohibits the use of antibiotics, unless no other option is available to prevent the animal from suffering.

Good Agricultural Practice (GAP)/Best management practices (BMP) are mostly described through standards or legislation. For instance, GAP 'in the use of pesticides includes the officially recommended or nationally authorized uses of pesticides under actual conditions necessary for effective and reliable pest control. It encompasses a range of levels of pesticide applications up to the highest authorized use, applied in a manner which leaves a residue which is the smallest amount practicable' (FAO and WHO 2014). With respect to, for instance, health management in livestock farming, GAP includes the prevention of entry of diseases onto the farm, an effective health management (e.g. record keeping, animal identification and monitoring), and the use of chemicals and medicines as described by IDF and FAO (2004).

In the EU, *Good Farming Practice (GFP)* and in the US, *Best management practices (BMP)* are used synonymously with GAP. National codes of GFP constitute minimum standards for farm management and serve as a precondition for payments to farmers in the context of *cross compliance*. Cross compliance is the attachment of environmental conditions to agricultural support payments (Baldock and Mitchell 1995) and is an obligatory element of the Common Agricultural Policy (CAP). In the EU, cross compliance as well as GAP rules are generally laid down in laws or legal guidelines.

Furthermore, recent studies suggest a new cropping system that is a combination of organic and conventional farming, the so-called 'mineral-ecological cropping system', where the application of synthetic fertilizer is allowed but the use of chemical-synthetical pesticides is not allowed. The idea is to combine best organic farming measures to control weeds, pests and diseases with best conventional farming strategies to provide the right amounts and forms of nutrients to the plants. Therefore, this new farming concept seeks to reduce negative envi-

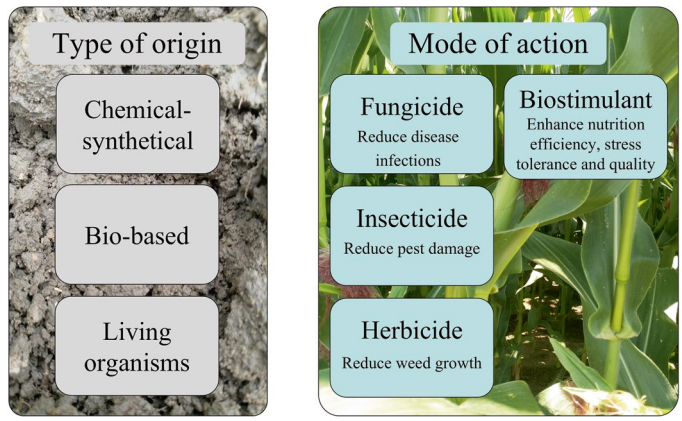


Fig. 6.17 Simple overview of plant protection measures with regard to their origin and mode of action. (© Moritz von Cossel)

ronmental impacts by avoiding the use of chemical-synthetical pesticides while maintaining an acceptable yield and quality level of the agricultural products (Zimmermann et al. 2021).

Technology Approaches

Conventional intensification approaches apply technical and biological innovations to increase productivity, to reduce the demand for agrichemicals, emissions or other environmental impacts of agricultural production. Examples for such innovations are more efficient or tolerant varieties derived from breeding programs, precision farming technologies or more effective and efficient fertilizer and crop protection substances.

Conservation farming mainly focuses on agronomical practices that enhance soil conservation via e.g. cover crops or incorporation of crop residues into the soil; here there might be a conflict with livestock in mixed production systems because livestock will compete for crop residues as feed and may compromise the objectives of conservation agriculture.

'Conservation Agriculture (CA) is an approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment. CA is characterized by three linked principles, namely:

- Continuous minimum mechanical soil disturbance.
- Permanent organic soil cover.
- Diversification of crop species grown in sequences and/or associations' (FAO 2017).

Precision farming strives to minimize agricultural inputs by applying spatially specific and targeted management to crops and accurate and timely feeding to animals using modern agricultural technologies including digitalization (see ▶ Chap. 15).

Precision farming makes use of modern agricultural production technology and is often computer-aided. In crop farming, the objective of precision farming is to take account of small-scale differences in management demand within fields. Sensors that assess the nutritional status and health of crops support their spatially differentiated management. Similarly, precision farming in livestock production aims at (continuous) monitoring of, for instance, the nutrition, performance, health and reproductive status of (individual or small groups of) animals in real-time. Such information helps farmers to make appropriate decisions in animal, feed or grazing management to optimize production, health and welfare of animals but also to increase efficiency of natural resource use in and reduce environmental impact of livestock farming.

Diversified farming makes use of the benefits of introducing several crops and animals in the production system instead of making use of only specializing in a single commodity.

Agroforestry combines annual cropping with trees and pasture systems (referred to as *agrosilvopastoral*) or tree species and annual crops (referred to as *agrosilvicultural*; see Excursus 6.1).

Natural Resource Conservation

Climate-smart agriculture (CSA) is described by the World Bank as an integrated approach to managing landscapes, cropland, livestock, forests and fisheries that addresses the interlinked challenges of food security and climate change. The three pillars of CSA are increased productivity, to produce more and better food, enhanced resilience of agricultural systems to reduce vulnerability to drought, pests, diseases and other climate-related risks and shocks and reduced GHG emissions. Applying precision farming approaches following GAP is a key for successful CSA.

Agroecology applies ecological concepts and principals in farming. Farming practices are applied that strive for mitigating climate change by reducing emissions, recycling resources and prioritizing local supply chains. The ambition is to work with nature through managing the impact of farming on wildlife and harnessing use of ecosystem services, such as pollinating crops and controlling pests. Furthermore, approaches led by local people and the adaption of agricultural techniques to suit the local setting with its specific social, environmental and economic conditions, are strived for. This holistic way of farming is defined by 13 principles (see ◘ Table 6.5) which serve as a guide towards

Table 6.5 Principles of agroecology according to Biovision (2019)

Principle	Description
Overarching goal: Improve resource efficiency	
Recycling	Use of local renewable resources, close resources cycles of nutrients and biomass
Input reduction	Reduce or eliminate dependency on purchased inputs and increase self-sufficiency
Overarching goal: Strengthen resilience	
Soil health	Secure and enhance soil health
Animal health	Ensure animal health and welfare
Biodiversity	Maintain and enhance diversity of species, functional diversity and genetic resources and thereby maintain overall agroecosystem biodiversity in time and space at field, farm and landscape scales
Synergy	Enhance positive ecological interaction, synergy, integration and complementarity among the elements of agroecosystems (animals, crops, trees, soil and water)
Economic diversification	Diversify on-farm incomes by ensuring that small-scale farmers have greater financial independence and value addition opportunities while enabling them to respond to demand from consumers
Overarching goal: Secure social equity	
Co-creation of knowledge	Enhance co-creation and horizontal sharing of knowledge including local and scientific innovation, especially through farmer-to-farmer exchange
Social values and diets	Build food systems based on the culture, identity, tradition, social and gender equity of local communities that provide healthy, diversified, seasonally and culturally appropriate diets
Fairness	Support dignified and robust livelihoods for all actors engaged in food systems, especially small-scale food producers, based on fair trade, fair employment and fair treatment of intellectual property rights
Connectivity	Ensure proximity and confidence between producers and consumers through promotion of fair and short distribution networks and by re-embedding food systems into local economies
Land and natural resource governance	Strengthen institutional arrangements to improve, including the recognition and support of family farmers, smallholders and peasant food producers as sustainable managers of natural and genetic resources
Participation	Encourage social organization and greater participation in decision-making by food producers and consumers to support decentralized governance and local adaptive management of agricultural and food systems

an improved collaboration with nature, a sustainable food system and a higher level of connection between farmers and consumers (Wezel et al. 2015; HLPE 2016, 2019; FAO 2018; Biovision 2019).

Within agroecology, the term 'agroecological intensification' was defined by Wezel et al. (2015) is 'a way of improving the performance of agriculture while minimising environmental impacts and reducing dependency on external inputs through integration of ecological principles into farm- and system management'. Practices applied can, for example, include mulching, intercropping, crop rotations, integrated soil- and nutrient management, soil- and water conservation, integrated pest management and biological control strategies and a balanced and more efficient use of fertilizers (Gambart et al. 2020). The overall aim is to produce healthy and enough food commodities. In the bioeconomy, residual biomass streams shall become 'couple products'. That requires a shift from the focus on the main products only to the overall optimization of all plant parts. In this way not only the main product but also the residual streams are obtained in the high qualities required for food and pharmaceutical processing or the use for bio-based products.

6.11.2 Sustainable Agricultural Intensification

In a future bioeconomy, agriculture will need to make combined use of all available knowledge and technology that can help increase productivity, while at the same time, reducing the negative environmental impacts of agricultural production. This vision is also described as 'sustainable intensification'.

The Royal Society (2009) defined sustainable intensification as a form of agricultural production (both crop and livestock farming), whereby 'yields are increased without adverse environmental impact and without the cultivation of more land' Pretty et al. (2011) extended this definition of sustainable agricultural intensification to 'producing more output from the same area of land while reducing the negative environmental impacts and at the same time, increasing contributions to natural capital and the flow of environmental services'.

6.11.3 Sustainable Intensification of Livestock Production

Examples from India and Kenya show that small changes in feeding practices like balancing diet with the same feed ingredients, feeding small additional amounts of concentrate, introducing cooling systems can greatly increase yields and total animal production, and the sustainability of the production systems (Garg et al. 2013; Upton 2000).

There is evidence that the nutrient use efficiency increases, while the intensity of methane emissions (g/kg milk) decreases by feeding nutritionally balanced rations designed from locally available resources in smallholders of cattle and buffaloes (Garg et al. 2013).

Even though challenging, larger improvements can be made in those production systems where the animal is still far from reaching its genetic potential for production, like those typically found in tropical and in developing regions.

Other intensification option is the more systematic use of agricultural or industrial by-products. However, one main problem of these materials is the unknown content of nutrients, therefore, a characterization of the available resources per region and their feeding value for each species may help to introduce them as ingredients in animals' diets. In this regard, even at the production units with high levels of intensification, advances towards sustainability can be made. In recent years the inclusion of citrus by-product from the juice industry has been regularly practiced in dairy cattle diets.

Moreover, later examples have shown that small proportions of crop residues like wheat straw and corn stover, as a source of physically effective fibre, can be included in diets of high yielding dairy cows without negative impacts on yields (Eastridge et al. 2017). Such by-products have been traditionally assumed

not to be suitable for diets of high yielding animals and have been rather associated in mixed systems with less productive animals.

The use of local forages as source of protein can also aid to the sustainable intensification of production systems. However, for a farmer to adopt any management practice, this has to fit into the farmer's daily routine or only minimally alter it, additionally, it should allow the farmer to afford it.

6.11.4 Criteria for Sustainable Agricultural Production and Biomass Supply

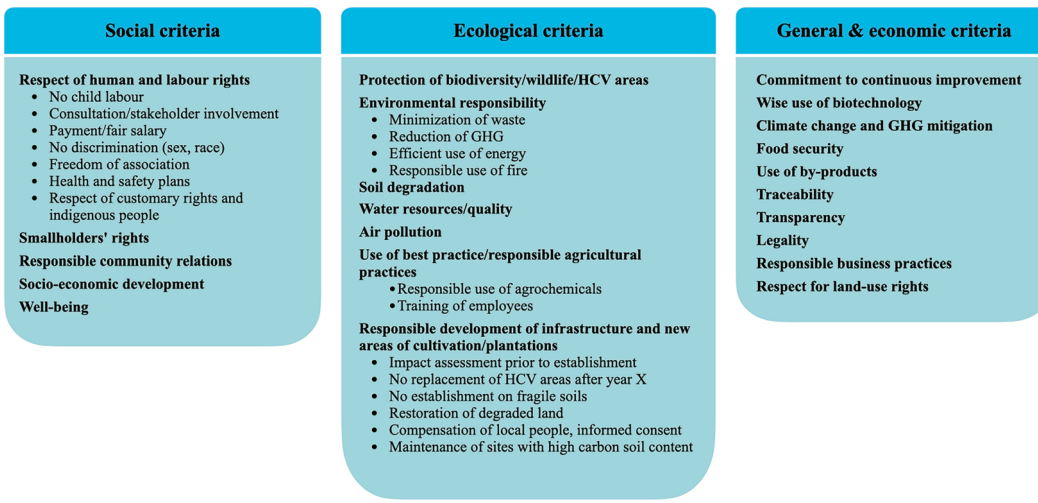
In order to define and describe the goals of sustainable agriculture, relevant criteria need to be established. Discussions in various international, multi-stakeholder roundtables have led to a set of internationally accepted criteria being compiled. The general criteria of the sustainability standards elaborated by these roundtables are shown in ◘ Fig. 6.18.

However, even if we manage to set the criteria for sustainable agriculture, the aspiration of 'absolute' sustainability appears inoperable. This is because the manifold trade-offs between sustainability goals and conflicting stakeholder perceptions of sustainability render the simultaneous fulfilment of all sustainability criteria shown in ◘ Fig. 6.18 impossible. Therefore, the concept of sustainable agricultural intensification will need to strive for the best possible compromise between productivity increase and natural resource conservation.

6.11.5 Increasing Agricultural Productivity

There are many options for increasing agricultural productivity. ◘ Figure 6.19 shows the numerous technical approaches that can contribute to this goal. These include breeding of efficient crop varieties and animal breeds; development of efficient, site-specific crop and livestock management and land use systems; development of specific feeding strategies for an animal type and region; logistic optimization; and exploration of new biomass resource options, such as algae and biomass from permanent grasslands.

The largest potential for maximizing yields through improved cropping and livestock systems is seen in approaches targeted at closing the yield gap between achievable and actually harvested yields. In many regions of Africa, Latin America and Eastern Europe, this gap



◘ **Fig. 6.18** Summary of criteria for sustainable agricultural production and biomass supply, compiled from the sustainability standards of the Roundtable on Sustainable Palm Oil (RSPO), the Round Table on Responsible Soy (RTRS), Bonsucro and the Roundtable on Sustainable Biomaterials (RSB). (Based on Lewandowski 2015)



Fig. 6.19 Technical and socio-economic options for mobilizing the sustainable biomass potential, allocated to different production scales in the bio-based value chain. (Based on Lewandowski 2015)

averages up to 55% (FAO 2002). The problem is often not the biophysical suitability of the site, 'site x crop combination' or production potential of livestock animals, but insufficient agronomical practices and policy support (Yengoh and Ardö 2014). However, to avoid the intensification of agricultural production necessary to exploit the yield gap becoming, or being perceived as, ecologically 'unsustainable', concepts for *sustainable intensification* need to be elaborated. In addition, advanced agricultural technologies, such as precision farming, that can improve productivity without negative ecological impacts, need to be further developed.

The provision of technical solutions for the improvement of cropping and livestock systems alone will however, not be sufficient to mobilize the sustainable biomass supply. Farmers must also be willing to adopt these solutions and see an advantage in their application (Nhamo et al. 2014). Also, farmers must be able to afford the agricultural inputs required and be in a position to apply them. This calls for support through credit programs and access for farmers to markets and training programs (Nhamo et al. 2014).

What constitutes sustainable agricultural production in your opinion?

6.11.6 Agriculture and Greenhouse Gas Emissions (GHG)

Agriculture also needs to contribute to climate change mitigation via a reduction of greenhouse gas (GHG) emissions. The main GHGs are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). In the year 2021, global agriculture emitted about 5.86 Gt $CO_{2\ equivalents}$ of GHGs (ClimateWatch 2025). CO_2 is mainly released from microbial decay or burning of plant litter and soil organic matter, but also comes from the use of fossil resources in agricultural production. CH_4 is mainly produced from fermentative digestion by ruminant livestock, from the storing of manure, and from rice grown in flooded conditions (Mosier et al. 1998). N_2O comes from nitrification and denitrification of nitrogen in soils and manures, or from nitrogen volatilization, leaching and runoff and its emission is enhanced with higher levels of nitrogen fertilization (for soils) or high levels of N feeding (for animals) (IPCC 2006).

The global technical potential for GHG mitigation in agriculture is estimated to be in the range of 4.5 to 6.0 Gt $CO_{2\ equivalents}$/year if no economic or other barriers are considered (Smith et al. 2007). In general, GHG emissions can be reduced by increasing plant and animal productivity (i.e. unit of final product per unit of area or per animal), and by more efficiently managing inputs into the system (e.g. applying the appropriate amount of fertilizer needed for a particular crop under the soil/climatic conditions, closing nutrient cycles). Other options include land management that increases soil carbon sequestration (e.g. agroforestry), improving diet quality to reduce enteric CH_4 formation, soil management that enhances the oxidation of CH_4 in paddy fields, and manure management that minimizes N_2O formation. Finally, also the use of bioenergy is a mitigation option (see Fig. 6.20; for details on agricultural GHG mitigation options, see Smith et al. 2007).

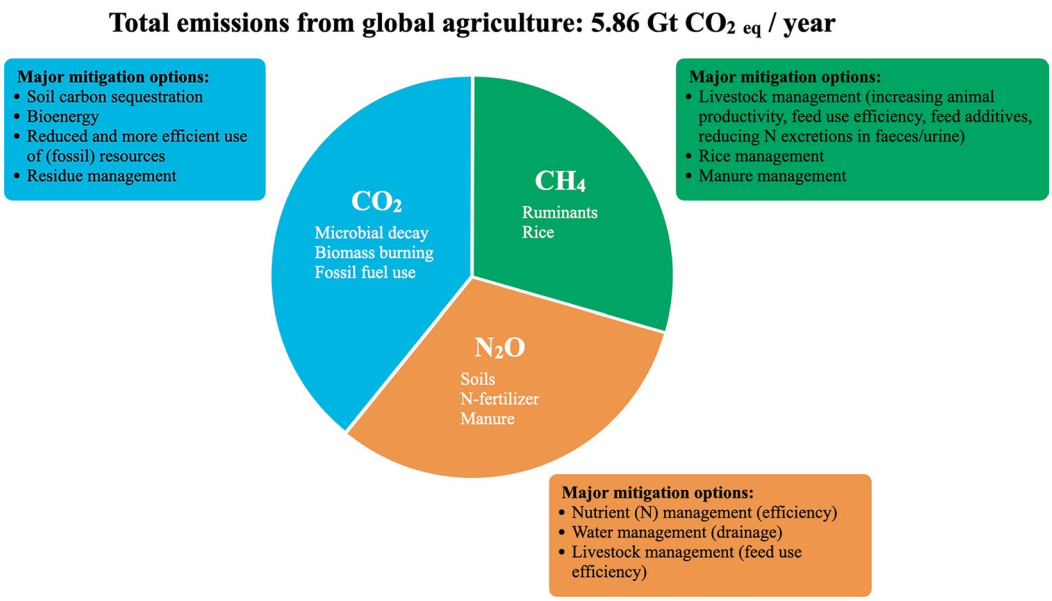


Fig. 6.20 Greenhouse gas emissions from global agriculture in Gt $CO_{2\ equivalents}$/year together with major emission sources. Boxes indicate major GHG mitigation options in agricultural management. (Based on data from Smith et al. 2007)

Questions

1. What is climate-smart farming? Name some important management practices.
2. How can the negative environmental impacts of agricultural production be minimised?
3. What are the factors that determine the yield that farmers can harvest from a crop?
4. What are the management options for improving efficiency and productivity in animal production?
5. What are the management options for improving efficiency and productivity in crop production?

Answers

1. Climate-smart farming strives to reduce the impact of agricultural production on global warming and for providing adaptation strategies to climate-change impacts.
   Management practices that help to reduce the emissions of greenhouse gases (GHG) from agricultural production include, among others:
   – the targeted application of nitrogen fertilizer (to reduce N_2O emissions)
   – improved livestock management, especially by increasing the productivity and optimizing manure management (to reduce CH_4 emissions) and
   – increased carbon contents in soil (to reduce CO_2 emissions), for example, through low till faming measure
   Adaptation strategies include management practices that improve the resilience of agricultural production systems against stresses, such as drought or flooding, or outbreak of pest and diseases. Diversification is an important strategy here and can be achieved by applying diverse crop rotations. Breeding of stress tolerant varieties and soil cultivation that maintains soil quality and water holding capacities are more examples for management options.
2. The negative environmental impacts of agricultural production can be minimised…
   – …by optimizing the agricultural production system in a way that minimizes the requirements of external inputs, for example, by crop rotations and circularity

- …by applying nitrogen and organic fertilizer timely and in appropriate formulations and amounts and modern technologies, such as precision farming.
- …by minimizing soil cultivation and applying the necessary operations that are timely enough to avoid soil erosion or damage, such as compaction.
- …by reducing demand for crop protection, for example, by choosing good crop rations and robust varieties, and by using biological or integrated pest management (IPM) approaches for crop health protection and weed control.
- …by improving efficiency of agricultural production (see e.g. Fig. 6.19), including the delivery of multiple ecosystem services.

These are major examples. But there are more management options that can help to reduce greenhouse gas emissions from agriculture (see Fig. 6.20) or support biodiversity, such as perennial cropping systems.

3. Factors that determine the yield that farmers can harvest from a crop are:
   - The site conditions, such as the quality of the soil and the climate, especially precipitation and temperature, and the risk of stresses, such as drought periods or floods,
   - The crop chosen and the management system applied, especially the access to modern varieties, fertilizer and crop protection means,
   - The available technology, for example, for low-loss harvesting,
   - The farmer's education and ability to optimize the crop production process.
4. Management options for improving efficiency and productivity in animal production are:
   - Choosing the suitable animal species and bred for the given environment.
   - Ensuring animals' well-being and health.
   - Optimizing Feed conversion Ratio (FCR) by providing nutritious and healthy feed.
   - Integrating animals into the farming system, for example, by recycling plant nutrients from slurry after slurry has been used for biogas production.
5. Management options for improving efficiency and productivity in crop production are:
   - Choosing the suitable kind of crop and variety for the given site conditions.
   - Providing optimal conditions for crop development through ensuring a good crops establishment, crop nutrition and crop health.
   - Avoiding losses during crop growth by defeating pests and diseases.
   - Optimizing the harvesting procedure, especially with regard to timing and in order to avoid harvest losses.

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Urban Agriculture

Bastian Winkler



Fig. 7.0 Urban agriculture (▶ https://doi.org/10.1007/000-htj)

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Urban agriculture (UA) is nowadays an important component of sustainable urban development. There are many types of urban agricultural activities that differ based on the intention and scale, the outputs generated, organisational forms and the people involved. Urban farming (UF) is performed by professionals with the aim of producing substantial amounts of food in modern cultivation systems under controlled environmental conditions in vertical indoor farms or rooftop greenhouses. On the contrary, urban gardening (UG) initiatives often use vacant urban spaces for the cultivation of diverse food crops and ornamental plants in self-made raised beds, boxes and containers. These gardening activities aim at the formation of communities that re-shape their neighbourhood, while sharing tools, knowledge and the produce. These groups support a healthy and sustainable lifestyle and often advocate for these topics on political level. Both types of UA are important for the bioeconomy as they serve multiple purposes. UF uses new areas and resource-efficient production methods to increase the biomass production, create new local value chains and business models. Diverse community gardens deliver a wide range of ecosystem services, such as city climate improvement, nutrient recycling from organic wastes, water retention, while supporting human health and social cohesion. Awareness is raised among consumers about fresh, healthy food, including the way of production, while bringing nature with its valuable ecosystem services (back) into cities. Various examples illustrate the diverse forms of urban agriculture as an important bioeconomy approach at the end of this chapter.

7

Learning Objectives

After reading this chapter, you will…

- …be able to explain the different types of urban agriculture (see ► Sect. 7.1).
- …be able to characterise urban production systems by describing the multiple, yet different outputs, goods and services they provide (see ► Sect. 7.2).
- …be able to explain the importance of urban agriculture for sustainable urban development and the societal transition towards the bioeconomy (see ► Sect. 7.3).

7.1 Definition and Types of Urban Agriculture

Urban agriculture (UA) grew from a trend into an important aspect of sustainable urban development within the last two decades (Gómez-Villarino et al. 2021). Actually food production in cities was needed for urban food security over centuries (Taylor and Lovell 2014), while it nowadays is recognised for its multiple private and public good and services provided (Lewandowski et al. 2024). According to the Food and Agriculture Organisation of the United Nations (FAO) 'Urban and peri-urban agriculture can be defined as the production of food and other outputs and related processes, taking place on land and other spaces within cities and surrounding regions' (FAO 2022).

> ***Urban and peri-urban agriculture*** refers to the production of food and other outputs and related processes, taking place on land and other spaces within cities and surrounding regions (FAO 2022).

However, behind this general, spatial definition is a huge variability of types and forms of UA. To get a better understanding of UA one needs to distinguish between private and community-based gardening activities as a leisure time activity (Urban gardening), and the production of large quantities of food and biomass crops under controlled-environment conditions in vertical indoor farms or (rooftop) greenhouses by an interdisciplinary team of professionals (Urban farming) (Winkler 2021; Alves and Oliveira 2022).

Urban gardening (UG) is typically a leisure time activity performed by interested urban inhabitant. Organisational forms of community gardens range from informal groups over

non-profit organisation to registered businesses. A survey-based study in Germany revealed that members of urban community gardens are a very heterogeneous group of people. City inhabitants of all ages, gender, origin (urban or rural), nationality and profession form urban gardening communities. What the majority (about 70%) has in common, is their higher education background (at least a Bachelor degree) (Winkler et al. 2019).

Urban community gardens often strengthen social cohesion in neighbourhoods through joint activities with a common purpose (Alves and Oliveira 2022). Besides crops, urban community gardens 'grow' transformative ideas for neighbourhood and city development, thereby fostering collective education and (political) action from the bottom-up beyond a garden's fence (Kropp and Müller 2018; Sashika et al. 2024).

Typical cultivation systems include raised beds, pots, containers, and, where possible, garden plots and mound cultures. Virtually any vacant private and public urban space on the ground or on rooftops is occupied (legally or not) through locally adapted cultivation systems (Sanyé-Mengual et al. 2019). The common denominator is soil-based cultivation and in many cases, organic fertilisation, thereby closing nutrient cycles by composting organic wastes and crop residues (McEldowney 2017; Winkler et al. 2019).

Urban farming (UF) is typically a business activity. Professionals are employed for the production of food and other biomass crops (e.g. pharmaceuticals) to supply it in large quantities to the urban population. The more advanced the production system is, the more interdisciplinary the teams of experts become, e.g. consisting of gardeners, technicians for automated cultivation technologies, software specialists for climate and light control, logistic experts, sales and marketing staff and all management related positions like accounting, human resources, etc.

Crop cultivation usually takes place in soilless production systems, covering hydroponics, aeroponics or aquaponics in space-efficient vertically stacked racks and gutters (Engler and Krarti 2021; Sashika et al. 2024). Water and nutrient supply is adapted to the crop needs and re-circulating. Indoor farming and (roof-top) greenhouses with controlled environment and artificial lighting allow for cultivation independent of outside climatic conditions and growing seasons. This combination of controlled environment agriculture (CEA) and re-circulating, vertically arranged cultivation systems show very high resource-use and space efficiencies (Kalantari et al. 2017; Al-Kodmany 2018).

These two types of UA are merely distinguished based on the scale of production, the prevailing cultivation systems, the organisational forms (non-profit; businesses) and the people performing it as their job or in their free-time. To capture the variability of UA and its immense potential as bioeconomic approach for sustainable (urban) development, the following chapter will highlight the multiple purposes and outputs including goods and products, ecosystem services as well as social, environmental and economic values generated.

7.2 Urban Agriculture as a Multi-purpose Bioeconomy Approach

The increase in agricultural biomass production (for food, feed, fibre and fuel use) at high resource-use efficiency rates, in light of the major agricultural challenges of the twenty-first century (see ▶ Chap. 1), is a major reason for UA, in particular UF. Garden activities on a private and community basis create multiple ecosystem services and social benefits:

7.2.1 Productivity and Yields of UA

The meta analysis of Payen et al. (2022) revealed similar and often higher yields from UA (UF and UG) compared to conventional, open-field agricultural systems for nearly all major crop categories defined in the FAOSTAT crops and livestock database (FAO 2024). For example, the yields of the crop categories 'fibre crops primary', 'roots and tubers', 'oil-crops' and 'vegetables primary' where found to be more than twice as high in urban cultivation systems. However, for the majority of

crops there is no difference between vertical and horizontal cultivation.

Soilless hydroponic cultivation systems, typical in UF, are in particular suitable for crops such like 'chilies and peppers' (> 6-times higher yields) and 'tomatoes' (> 2.5-times higher yields), while 'lettuce and chicory' and 'cucumbers and gherkins' reach significantly higher yields (up to 2-times higher yields). Controlled environment agriculture (CEA) always resulted in higher yields. This can be attributed to the accurately adapted cultivation conditions to each crop (e.g. water and nutrient supply) and pest management. CEA with artificial lighting leads to the highest 'lettuce and chicory' as well as 'cabbages and other brassicas' yields, while 'tomatoes' favour CEA with sunlight (Payen et al. 2022). This meta-analysis (so far the only one) underlines the importance of UA for food security and the production of biomass with valuable ingredients for the growing bioeconomy.

Controlled Environment Agriculture (CEA) is the production of plants, algae, fungi, insects, shrimp and fish in an almost closed-loop setting in greenhouses, growth chambers, vertical farms, or any other structure that provides a controlled environment. To provide the organisms with optimal growth conditions, the main parameters that need to be controlled are temperature, light, water and nutrient supply, humidity, and carbon dioxide. Many CEA systems, such as hydroponics, aeroponics, aquaponics and microalgae production, are soilless systems and therefore do not require agricultural land. Various technologies are applied to control the conditions in CEA systems, including robotics, sensors, big data analytics, artificial intelligence (AI) and the Internet of Things (IoT).

7.2.2 Resource-Use Efficiency

The resource-use efficiency of UA very much depends on the type of cultivation system. Soilless cultivation systems applied for UF are designed to maximise resource use efficiency. In contrast to soil-based, open-field agriculture, the cultivation environment is 'designed' around the crops' needs. Providing light intensity, temperature, humidity, water (incl. pH), nutrients (incl. CO_2 concentrations) and ventilation rates in such a way allow for optimal crop productivity (Engler and Krarti 2021; Alves and Oliveira 2022; Oh and Lu 2023). The intended segregation between the outside environment and controlled environment (incl. the absence of soil) further protects the crops from pests and diseases. In addition, sophisticated hygiene concepts and internet of things (IoT) sensor-based crop monitoring (see ▶ Chap. 15) allows for early pest and disease detection (Sashika et al. 2024), reducing crop stress and failure.

The re-circulation of the nutrient solution (incl. filtration, e.g. with UV light) in hydroponic systems can reduce the water demand by 70–95% (Engler and Krarti 2021) and the fertiliser amounts by 55–85% (AlShrouf 2017) compared to conventional, open-field agriculture.

In the future, the integration of artificial intelligence (AI) into farm control systems (e.g. machine learning, deep learning, image processing and computer vision) (see ▶ Chap. 15) (Rathor et al. 2024; Sashika et al. 2024) will likely increase the resource-use efficiency further. Nutrient recovery from urban organic wastes for organic hydroponics will render these systems more sustainable by contributing to resource circularity (Park and Williams 2024) and providing a basis for circular bioeconomy hubs (EC 2018).

7.2.3 Ecosystem Services

In particular, UG activities on a private and community basis benefit the environment and the society in multiple ways (see Excursus ▶ 6.4).

Private and community gardening is ranking among the top five leisure-time activities of city inhabitants, including recreation, biking or eating out (Ambrose et al. 2020), and therefore provides a crucial cultural service. Turning vacant spaces into community gardens not only increases pro-environmental behaviour,

but even reduces violence and crime, in particular in low-income neighbourhoods (Ogletree et al. 2022; Benjumea Mejia et al. 2024). Other cultural ecosystem services of UG encompass the connection of humans with each other, the re-connection of humans with nature, education related to gardening practices as well as the aesthetic appearance of the neighbourhood. A representative study from Miami (USA) revealed these ecosystem services to rank highest among the public (Zhao et al. 2024).

Further, UG typically inhabits a variety of food and ornamental plants in soil-based cultivation systems. Such multi-cropping systems therefore provide habitats for a diverse flora and fauna. For example, 707 plant species were recorded in a community garden in Los Angeles (Clarke and Jenerette 2015), while a garden in Tel Aviv was home to 65 bird species (Paker et al. 2014).

From an urban planning perspective, regulating ecosystem services are important for improving microclimate and air quality, reduce heat islands and retain water in case of heavy rainfalls. Urban vegetation (including UA areas and green roofs) can decrease the ambient temperature by 0.5 to 4.0 °C (Qiu et al. 2013), while effectively absorbing air pollutants (incl. NO_2, SO_2, O_3 and particulate matter) at a rate of 85 kg per hectare and year in Chicago (USA) (Yang et al. 2008). Tilled soils amended with compost at a ratio of 2:1, as often done in UG, double their water holding capacity and increase the total water storage capacity up to 65% (Ebissa and Desta 2022). This results in reduced/delayed peak flows in case of heavy rains and urban water management systems.

7.2.4 Linking Consumers and Producers in a Growing Bioeconomy

Both types of urban agriculture connect consumers and producers and the environment.

UF brings food production (back) to the cities. In many cases the produce of the farms is sold directly (John and Artmann 2024), e.g. in in-house stores or are delivered to the customers in boxes on subscription basis. Very large vertical farms are capable of distributing the produce via retailers such as supermarkets. The (hyper-)local production is advertised as part of the marketing strategy of vertical farming business, informing the consumers about the production of food that allows for more informed consumer choices. In both cases food production in cities reduces food miles and related CO_2 emissions (Alves and Oliveira 2022).

The participants of urban community gardens learn about all aspects of cultivation. Inputs such as soil, water, fertiliser and pest management as well as the labour (incl. tools) and necessary timing (e.g. watering, fertilisation, etc.) become part of the gardening activities and eventually part of the life styles. Cultivation knowledge and practical know-how are exchanged and passed on within the garden communities, supporting social interaction and cohesion (John and Artmann 2024). Moreover, urban community gardeners in German expressed in a survey that they changed their food consumption behaviour. Since they started urban gardening, they purchase 26% more organic, 35% more regionally and 42% more seasonally produced food (Winkler et al. 2019). Hence, UG is capable of bridging the gap between production and consumption and is therefore an important measure for involving urban inhabitants in the societal transition towards a sustainable bioeconomy.

The various forms of UF and UG cover multiple, necessary aspects for growing the bioeconomy: New areas are exploited for a highly resource-efficient biomass production through UF, while multiple ecosystem services are provided by UG in form of nature-based solutions. Both forms are capable of addressing and providing solutions for social and environmental challenges. Consequently, urban agriculture is integral part of the bioeconomy.

7.3 Examples of Urban Agriculture

Urban farming comprises a variety of indoor cultivation systems of different scales including (roof-top) greenhouses and vertical farms (sometimes called plant factories) and variety

of crops cultivated in typically soilless production systems:

The production of microgreens (or sprouts) is a typical indoor cultivation system. In short cultivation cycles of about 10 days a wide variety of microgreens are produced in cities. The microgreens are delivered on regular basis to restaurants and canteens or are offered often directly at the microgreen farm to private customers.

The *Kleinblatt GmbH* in Stuttgart (Germany) is an example for a 'hyper-local' indoor farm (Fig. 7.1). Microgreens including radish, peas, cabbages and others are produced in-store and delivered via freight-bikes to multiple restaurants several times a week. The cultivation takes place on self-designed, re-usable trays with automated irrigation. The seeds are sown in high-density on organic hemp mats. After harvest of the microgreens, the hemp mats (incl. roots) undergo a cascade-use and become the substrate for the production of edible mushrooms. This is a perfect example for urban farming system based on bioeconomic principles.

Indoor cultivation systems are vertical farms of various scales. Typically, old or unused buildings are transformed into cultivation systems using racks of different shape and design to cultivate crops vertically on top of each other and on several stories of a building.

The Smart Office Farm, a research and development unit (Fig. 7.2), was prototyped to enable office employees to grow their own fresh vegetables and herbs inside the office with minimum effort and background knowledge on cultivation (Cichocki et al. 2022).



Fig 7.1 Vertical microgreen production at the urban farm of Kleinblatt GmbH in the city centre of Stuttgart, Germany. (© Kleinblatt GmbH)

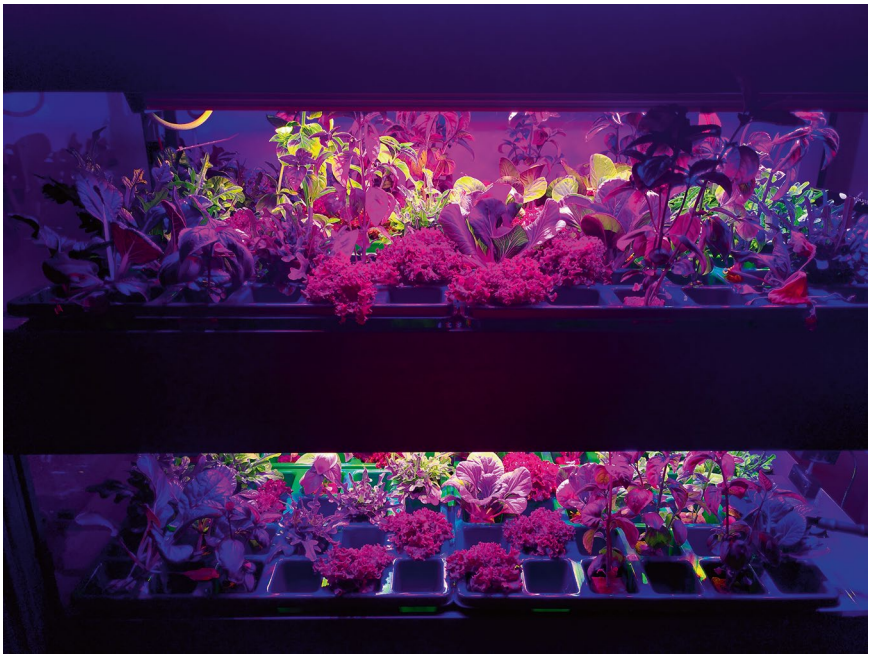


Fig 7.2 Lettuce and herbs grown by employees in an automated vertical indoor farm with Ebb&Flow cultivation system. (© Bastian Winkler)

Modern greenhouses produce larger quantities of leafy and fruit vegetables as well as fresh herbs within or in the surroundings of cities. Typically, re-circulating soilless cultivation systems such as nutrient film technique (NFT), ebb & flow, deep water culture (DWC), Dutch buckets or channels with drip-irrigated substrate mats are employed. Soilless cultivation systems use space, water and nutrients very efficiently (Kalantari et al. 2017; Sashika et al. 2024). As substrates, peat, rockwool and coconut coir are mainly used; however, this poses sustainability challenges. Peat extraction causes the destruction of biodiverse and CO_2-negative wetlands, rockwool requires very high temperatures (> 1500 °C) for its production, while coconut coir is produced in (sub-)tropical countries and requires long-distance shipping (Gruda 2019). Substrates and fertiliser are among the main inputs for soilless cultivation, the main sustainability challenges arise here (Barrett et al. 2016). Many bio-based materials (e.g. miscanthus, willow) and organic residues and wastes have been tested and evaluated, however, with limited success. Soilless cultivation systems require uniform and inert materials—characteristics that organic material cannot achieve by nature (Barrett et al. 2016; Gruda 2019). Therefore, industrial textiles (from fossil resources) are a promising alternative substrate because they are produced in large quantities, are chemically inert, are durable and can be equipped with defined characteristics (Fig. 7.3). Circularity is achieved by the additional development of cleaning processes to allow for multiple re-use. After the end-of-life, the fossil resource-based textile can be fully recycled (CirCulTex 2024).

Urban gardening is performed by city inhabitants either on private basis, for example, in traditional home gardens, on balconies and roof terraces as well as part of urban community gardens as joint activity with neighbours.

Pots, containers and raised beds are typically used to plant edible and ornamental crops on private roof-tops, balconies and yards. Companies have specialised on urban planting systems, like 'HariMitti Agro Pvt. Ltd.' at Kolkata, India (Fig. 7.4). They are a one-stop shop for urban gardening providing light-weight raised beds of different sizes, selected seeds and seedlings, maintenance ser-



Fig 7.3 Greenhouse cultivation of Basil and Pak Choi on re-useable textile substrate in a Nutrient Film Technique (NFT) system at the University of Hohenheim. (© Bastian Winkler)



Fig 7.4 Roof-top garden with raised beds planted with vegetables, herbs and flowers in Kolkata. (© HariMitti Agro Pvt. Ltd.)

vice and an adapted compost-based soil mixture. For the latter, HariMitti Agro collects organic kitchen wastes from their customers, vermicomposts them and uses the vermicompost as nutrient-rich amendment for the potting soil of the raised beds – a circular bioeconomy approach that creates new cultivation areas, promotes waste separation and recycles nutrients.

An advanced method for the organic cultivation of food and ornamental crops are circular terrabioponic garden systems



Fig 7.5 Circular terrabioponic garden system at a sealed interior yard of a company for the production of fresh tea herbs and flowers to support biodiversity. (© Geco-Gardens GmbH)

(Fig. 7.5). These garden systems connect cultivation and decomposition according to the natural cycle. Nutrients for the crops are recycled from organic household wastes by vermicomposting (= bio). Thereby a solid and a liquid compost fraction are created. The liquid fraction is mixed with irrigation water. This organic nutrient solution ('vermitea'), containing nutrients and beneficial microorganisms, is directed to the crops via a solar-driven underground irrigation system (= ponic).

The solid vermicompost is added to the potting soil (= terra). These autonomous and modular garden systems are adaptable to fit balconies, rooftops and interior yards and allow for urban food production on basically any sealed surface based on the available resources: sunlight, water and organic waste (Winkler et al. 2019).

In urban community gardens, people with diverse backgrounds gather for joint gardening in often very biodiverse, soil-based cultivation systems. Social exchange and collaboration as well as a wide range of ecosystem services are created, like, for example, at 'Inselgrün' (about 600m^2) in Stuttgart (Fig. 7.6). The total value of the community gardens' ecosystem services provided to the public was estimated to be as high as 280,000 €. In the garden 900kg of food are produced with a value of about 1200€, while 70kg of $CO_{2\text{-eq.}}$ (worth 10€ annually) are mitigated and 2000 litres of water are retained (worth 90€ annually). The main value generated by the community garden is of a social nature and comprises social cohesion among the neighbours and therapeutic activities of marginalised groups (Gartenleistungen 2022).



Fig 7.6 Community garden Inselgrün in Stuttgart comprising more than 80 self-built raised beds with numerous vegetables, herbs, flowers, shrubs and trees cultivated. (© Bastian Winkler)

7

Questions

1. What are the two main types of urban agriculture (UA), and how do they differ in terms of scale, purpose and organisational form?
2. How do urban gardening (UG) and urban farming (UF) contribute differently to the outputs, goods and services provided by urban agriculture?
3. Why is urban agriculture (UA) important for sustainable urban development and the societal transition towards a bioeconomy?

Answers

1. The two main types of urban agriculture are urban gardening (UG) and urban farming (UF).
   a. Urban gardening (UG) is typically a leisure activity undertaken by urban residents, often organised informally or through non-profit organisations. It focuses on small-scale, soil-based cultivation systems such as raised beds, pots, and containers. Its primary purpose is social and cultural, such as fostering community cohesion and providing education.
   b. Urban farming (UF) is a business-oriented activity carried out by professionals. It involves large-scale food and biomass production using advanced, soilless systems such as hydroponics and vertical farming. UF prioritises resource-use efficiency and controlled environment agriculture (CEA) to maximise yields.
2. Urban gardening (UG) primarily generates social and environmental benefits. It strengthens community ties, provides cultural ecosystem services, and supports biodiversity by creating habitats for plants and animals. UG also promotes sustainable lifestyles by encouraging participants to adopt pro-environmental behaviours and consume more organic, regional, and seasonal food. Urban farming (UF) focuses on efficiently producing large quantities of food and biomass. Through advanced technologies like hydroponics, UF achieves higher yields for specific crops, reduces resource use and offers hyper-

local produce with lower carbon footprints. UF also contributes to the bioeconomy by producing crops with valuable ingredients for food, pharmaceuticals and other products.

3. Urban agriculture integrates food production into urban spaces, promoting sustainability and circularity. It supports urban development by reducing food miles, cutting CO_2 emissions, and reusing organic waste as compost or nutrient sources. UG enhances social cohesion and educates urban inhabitants on sustainable consumption practices, while UF employs resource-efficient methods to address global challenges such as food security and resource scarcity. Together, UG and UF help cities transition towards a bioeconomy by providing solutions to social, environmental, and economic challenges.

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Forestry

Gerhard Langenberger and Melvin Lippe



Fig. 8.0 Forestry. (© Gerhard Langenberger) (▶ https://doi.org/10.1007/000-htk)

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Forests are an important component of the global bioeconomy. They cover approximately 31% of the Earth's total land area, equivalent to 4.06 billion hectares, and are home to the majority of the world's terrestrial biodiversity. Forests also store nearly as much carbon as the atmosphere does. They serve numerous functions, including providing livelihoods for more than a billion people, conserving biodiversity, soil and water, and supplying wood for energy, construction and other uses. Additionally, they offer a range of bio-based resources and materials, such as food and feed. Forestry was the first sector to introduce the concept of sustainability, initially described by Carl von Carlowitz in 1713 in his published book 'Silvicultura oeconomica' (Schmidthüsen 2013). The sustainable use and management of forests is still a very important issue today. Forestry is a multi-functional bioeconomic system that supports the manufacture of products and energy sources which are bio-based, renewable and environmentally friendly. Thus, forests play an important role in securing a sustainable resource base for the current and future bioeconomy. However, forests face significant threats from climate change and anthropogenic impacts, leading to net annual loss of nearly 5 million hectares, primarily due to conversion to agricultural land.

Learning Objectives

After studying this chapter, you will…

- …be able to assess forests as ecosystems in their own right, and as a crucial component of a bioeconomy (see ► Sects. 8.2 and 8.6).
- …be able to name the main types of forests and their specific characteristics (see Sects. ► 8.1 and ► 8.6).
- …be able to explain why forests are important multifunctional ecosystems and production systems and how they contribute to maintaining ecosystem services (see ► Sects. 8.2 and 8.3).
- …be able to describe the characteristics and specificities of forest management (see ► Sect. 8.4).
- …be able to explain why forest products are of significant importance to the bioeconomy (see ► Sects. 8.3 and 8.7).
- …be able to enumerate the challenges forests continue to face, as well as the approaches that exist to conserve and regenerate forest areas (see ► Sects. 8.4 and 8.5).

8.1 Forests and Forestry

Forestry is the science and practice of forest management. It includes the use of both natural and near-natural forests as well as tree plantations. Semi-natural forests are those forests in which the original tree species composition and forest ecological dynamics are still largely preserved. The artificial creation of forests, following the recent or historical removal of the original forest cover - referred to as 'afforestation', 'reforestation' or 'assisted natural regeneration (ANR)'—is becoming increasingly important. This process can involve native tree species that were part of the original forest cover or so-called exotic tree species, which originate from other ecosystems and, often, other continents. While the latter was often criticised in the past as a distortion of the flora, the introduction of exotic species is currently being widely debated in the context of climate change and the associated, often drastic, changes to original habitats. Forestry, therefore, involves the use, management, protection and regeneration of forests (FAO 2018).

Forestry involves the management of forest ecosystems for a variety of purposes, including:

1. Timber Production: Harvesting trees for wood, paper and other products.
2. Reforestation and Afforestation: Planting trees to restore deforested areas (reforestation) or to create new forests in areas where none previously existed (afforestation).
3. Conservation: Protecting forests to preserve biodiversity, protect wildlife habitats and maintain ecological balance.
4. Water and Soil Protection: Forests play a key role in maintaining water quality and preventing soil erosion.
5. Climate Regulation: Acting as carbon sinks, forests absorb carbon dioxide from the atmosphere, helping to mitigate climate change.

6. Recreation: Managing forests to provide spaces for outdoor activities like hiking, camping and tourism.

In addition to these functions, forestry encompasses policies, laws and practices aimed at balancing economic, environmental, and social needs, ensuring the long-term health of forest ecosystems (FAO 2020a, 2024; IPCC 2007, 2022).

There is a consensus that forests are composed of trees. But when can a collection of trees be described as a forest? Are trees lining a road or an avenue already a forest? Are Mediterranean olive groves or eucalyptus plantations considered forests? Can recreational parks with scattered trees, such as the 'Central Park' in New York or the 'English Garden' in Munich, be defined as forests? At first glance, these questions might seem irrelevant, as the purpose of such areas is often clear - they are not typically used for timber production, for instance. However, other tree-covered areas may not be defined as parks, but still fulfil similarly important conservation or recreational purposes, such as the ► Frankfurt City Forest or Singapore's 'Botanic Gardens'.

A general definition of a forest could include the following criteria:

- Forests consist of a collection of trees, which are woody, upright, perennial plants.
- They develop a so-called 'forest climate' that differs considerably from that of the open land. This climate is characterised by reduced temperature fluctuations and extremes, lower wind speeds and higher relative humidity.

These conditions result in characteristic soil properties, typically with a high organic matter content. The various forest types, with their unique vertical structures create a wide range of habitats and ecological niches, forming the foundation for high biodiversity levels.

Since forests play an important role in the bioeconomy—for carbon storage, climate change mitigation and other purposes—a universal definition is essential for global analyses and statistics. To address this need, the Food and Agriculture Organisation (FAO) of the United Nations has defined general criteria for the classification of forests (FAO 2023a). However, as forests are dynamic and heterogeneous ecosystems, multiple definitions exist (cf. CBD 2006, online).

> ***Forests***, according to FAO (2023a), are defined as:
>
> - Land spanning more than 0.5 hectares with trees taller than 5 meters and a canopy cover of more than 10 percent, or trees capable of reaching these thresholds in situ (◘ Fig. 8.1).
> - It does not include land that is predominantly under agricultural or urban land use, as fruit tree plantations, oil palm plantations, olive orchards and agroforestry systems when crops are grown under tree cover, or short rotation coppice plantations.
> - Forest can be divided into two major categories: 'naturally regenerating forest' is a forest predominantly composed of trees established through natural regeneration, and 'planted forest' - a forest predominantly composed of trees established through planting and or/deliberate seeding.
> - Bamboo, mangrove and rubber wood stands are classified as specific forest categories.

Altogether, 93% of the global forest area consists of naturally regenerating forests, while 7% comprises planted forests (FAO 2020b). The forest definition by FAO is globally applicable and is used as guiding indicator for the ► Forest Resource Assessment (FRA) which is published every five years by FAO to report on the global and national status of forests. However, individual reporting countries are allowed to use their own national forest definitions, which may differ from the FAO's. For instance, Ecuador defines a forest as having a minimum size of 1 ha, a tree height of at least 5 meters, and a minimum canopy cover of 30% (FAO 2020b). In contrast, Germany's legal definition, as stated by the ► German Law of Forest, describes a forest as 'an area that is stocked

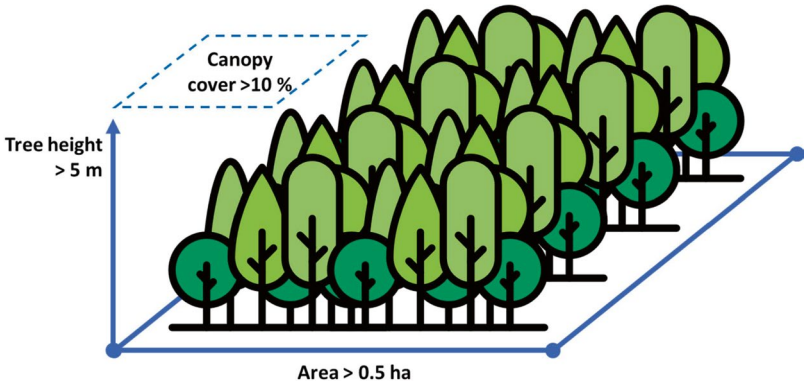


Fig. 8.1 Key features of the FAO forest definition

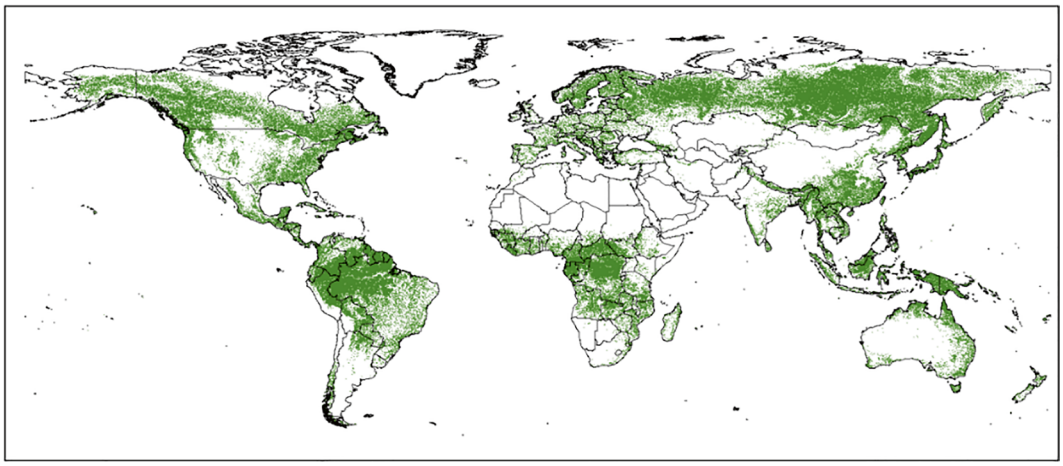


Fig. 8.2 Global extent of forest areas (based on Bourgoin et al. 2023)

with forest plants' and allows for size variations if the area exhibits forest-type habitats.

8.2 Forest Distribution, Floristic Regions and Forest Types

8.2.1 Global Forest Distribution

Historically, most regions of the Earth with a suitable climate—characterised by sufficient water availability and minimum length of growing season—were originally covered by forests (Ellis et al. 2010). However, since the beginning of human colonisation, forests have been exploited for resources and cleared, particularly for agricultural production (cf. Albion 1926). Figure 8.2 provides an overview of the global distribution of forests and Table 8.1 presents the forest cover by region while Table 8.2 lists the countries with the largest forest areas. Currently, the world has a total forest area of 4.06 billion hectares (ha), which is 31 % of total land area. Forests in the tropical climate domain exhibit the largest share of the world's forest (45%), followed by boreal (27%), temperate (16%) and subtropical (11%) climate domains (FAO 2020a).

Table 8.1 Global Forest area and regional distribution (based on FAO 2020a)

Region/subregion	Forest area 1000 ha	% Total forest area
Eastern and Southern Africa	295,778	7.3
Northern Africa	35,151	0.9
Western and Central Africa	305,710	7.5
Total Africa	636,639	15.7
East Asia	271,403	6.7
South and Southeast Asia	296,047	7.3
Western and Central Asia	55,237	1.4
Total Asia	622,687	15.3
Europe excl. Russian Federation	202,150	5.0
Total Europe	1,017,461	25.1
Caribbean	7,889	0.2
Central America	22,404	0.6
North America	722,417	17.8
Total North and Central America	752,710	18.5
Total Oceania	185,248	4.6
Total South America	844,186	20.8
World	4,058,931	100

Table 8.2 Top 10 countries in terms of forest area (based on FAO 2020a)

Ranking	Country	Forest area 1000 ha	% of world forest area
1	Russian Federation	815,312	20
2	Brazil	496,620	12
3	Canada	346,928	9
4	United States of America	209,795	8
5	China	219,978	5
6	Australia	134,005	3
7	Democratic Republic of Kongo	126,155	3
8	Indonesia	92,133	2
9	Peru	72,330	2
10	India	72,160	2

8.2.2 Floristic Kingdoms and Forest Types

8.2.2.1 Floristic Kingdoms

There are several approaches to differentiating and classifying the Earth's natural vegetation, with a key criterion being the floristic distinctiveness of an area. One major classification system, based on endemicity and the presence or absence of taxa, is the concept of floristic kingdoms. This idea was first proposed by Good (1947) and later expanded by Takhtajan (1986). Floristic kingdoms are large regions of the world that share similar plant life and ecological characteristics. They reflect the global distribution of plant species based on evolutionary relationships, climate, and geography. Within each floristic kingdom, forests are crucial ecosystems that provide diverse habitats and contribute significantly to biodiversity. Based on this concept, six floristic kingdoms are recogniszd: the Holarctic, Neotropical, Palaeotropical, Australasian, Capensian, and Antarctic kingdoms. These are further subdivided into floristic regions and provinces. As these kingdoms represent important groups of species, they also indicate the general usability of the associated forests, highlighting their bioeconomic potential. Understanding floristic kingdoms is helpful in the conservation and sustainable management of forest ecosystem, as each region has its unique characteristics and challenges. These forests play a crucial role in maintaining ecological balance, providing habitat for countless floral and faunal species, and supporting the livelihoods of local populations and wellbeing of societies in general.

The following overview of the floristic kingdoms lists plant groups of major economic importance together with their common use:

Holarctic Kingdom

- Location: encompasses the northern regions of North America, Europe, and Asia, covering vegetation in the northern hemisphere beyond the tropics and subtropics
- Major forest types: boreal forests (Taiga) and temperate forests

This vast region is characterised by representatives of key timber tree families. Notable examples include the pine family (Pinaceae), which features firs (*Abies* spp.), larches (*Larix* spp.), and pines (*Pinus* spp.), as well as several broad-leaved families such as the beech family (Fagaceae), which includes beech (*Fagus* spp.), oak (*Quercus* spp.), and chestnut (*Castanea* spp.); the birch family (Betulaceae), with birch (*Betula* spp.), alder (*Alnus* spp.), and hornbeam (*Carpinus* spp.); and the willow family (Salicaceae), which encompasses poplar (*Populus* spp.) and willow (*Salix* spp.). The Holarctic is also a centre of diversity of the rose family (Rosaceae) with its cherries (*Prunus* spp.), apples (*Malus* spp.), and peaches (*Pyrus* spp.). In particular, *Prunus* spp. play an important role in the forest bioeconomy as source of valuable hardwood.

Neotropical Kingdom

- Location: Central and South America, the Caribbean and parts of Mexico
- Major forest types: tropical rainforests and seasonal forests

Tropical rainforests are found in the Amazon Basin and are among the most biodiverse on the planet, hosting thousands of species of trees, plants and animals. Seasonal forests occur in areas with distinct wet and dry seasons. The Neotropics are also the origin of valuable hardwoods like mahogany (*Swietenia mahagoni*) (cf. Anderson 2012). Additionally, the Amazon region is the place of origin of the by far most important source of natural rubber, the Para rubber tree (*Hevea brasiliensis*).

Paleotropical Kingdom

- Location: Africa (excluding the northern deserts), Madagascar and parts of Southeast Asia.
- Major forest types: tropical moist forests, seasonal forests and mangrove forests

Tropical moist forests are found in regions such as the Congo Basin and are rich in biodiversity, supporting a variety of hardwood trees. Mangrove forests, on the other hand, are coastal forests in tropical and subtropical

regions that thrive in saline environments, providing critical habitat for marine life.

The Paleotropical Kingdom is particularly important as the origin of the ► Dipterocarpaceae family, which consists of several hundred species of timber trees. This family provides valuable tropical woods such as ► meranti, ► kapur and ► balau (Wagenführ 1996). The ► Combretaceae family is another significant source of timber, including species like *Terminalia* spp. (framiré, limba). Additionally, the Paleotropical realm is a centre of diversity for figs (► Moraceae).

Australian Kingdom

- Location: Primarily Australia, New Zealand and the surrounding islands.
- Major Forest types: eucalyptus forests and temperate rainforests

Eucalyptus forests are characteristic of Australia and are dominated by eucalyptus species, which are well adapted to dry conditions and periodic wildfires. Temperate rainforests, found in New Zealand and parts of Tasmania, are lush and moist, dominated by species such as podocarps and ferns.

The Australian kingdom is the origin of important plantation-tree species, particularly *Eucalyptus* spp. (Myrtaceae family), which is a crucial source of pulpwood. Additionally, it is a centre of diversity for *Acacia* spp. (Fabaceae family), which also play an important role in tropical tree plantations.

Capensis

The Capensis region is more significant as source of ornamental plants than for comercial forestry. It is a centre of diversity for the heath family (Ericaceae).

Antarctic Kingdom

- Location: Southern parts of South America, Africa, Australia, New Zealand, and surrounding subantarctic islands.
- Major Forest Types: temperate rainforests and subantarctic forests.

Temperate rainforests are found in areas of Chile and New Zealand, characterised by high rainfall and species such as southern beeches and giant tree ferns. Subantarctic forests, located on islands and coastal regions, are composed of resilient species capable of withstanding harsh conditions.

The Antarctic kingdom includes a tree group of mainly regional importance to the forest bioeconomy: the southern beeches (*Nothofagus* spp.).

8.2.2.2 Major Forest Types

While plant kingdoms refer to taxonomic distinctiveness, reflecting evolutionary processes rather than habitat homogeneity, forest types reflect environmental conditions and represent an important classification for understanding ecology, productivity and management options.

Boreal Forests

Boreal forests cover about 13% of the Earth's land surface. They are found in the northern hemisphere, primarily between 50 and 70° north, and consist of vast conifer-dominated forests in northern Europe, northern Russia, Canada, and Alaska, often referred to as taiga. To the south, they transition into temperate mixed and broad-leaved forests. These forests are characterised by a cold-humid climate, with annual precipitation between 250 and 500 (750) mm, mainly occurring during summer. Despite the very low regional precipitation, the hydrological balance is generally positive due to low evapotranspiration. The area experiences extreme temperature fluctuations and features permafrost soils, with average annual temperatures falling below 0 °C. The vegetation period typically lasts 3–5 months, with a maximum of 6 months. The forests are generally single-layered, with tree heights reaching up to 20 m. Species diversity is relatively low, with dominance by pine trees (*Pinus* spp., *Picea* spp., *Larix* spp., *Abies* spp.) and wind-pollinated broad-leaved trees (*Betula* spp., *Populus* spp.). The undergrowth is dominated by dwarf shrubs (e.g. *Vaccinium*), mosses, and lichens. Ectomycorrhiza plays a crucial role in this type of ecosystem. Since these forests typically grow on old landmasses, such as the Canadian shield, the soils are rather poor (e.g. podzols) and considerable

surface humus layers (cf. the occurrence of mosses and *Vaccinium*) can be found. Fire plays a considerable role in these forests. It transforms the accumulated biomass into nutrient-rich ashes and thus initiates the natural regeneration of the forests (Fig. 8.3). Due to their homogeneity and species composition, these forests are a significant resource for pulp and paper production (Kellomäki 2024).

Temperate Forests

Temperate forests cover about 8% of the Earth's land surface. Like boreal forests, they primarily occur in the northern hemisphere, found between 35 and 55° north, depending on macroclimatic conditions. The mountain forests of Patagonia and New Zealand can be named as examples of temperate forests in the southern hemisphere. These forests are characterised by more moderate climatic conditions than boreal forests. They are humid, with annual precipitation between 500 and 1000 mm, peaking in the summer. Temperate forests experience frost periods, but with much less pronounced extremes. The average annual temperature ranges between 5 °C and 15 °C, and the vegetation period lasts between 5 and 8 months. These forests exhibit a pronounced seasonality, often displaying gorgeous autumn colours, such as during the 'Indian summer' in the northeastern US and Canada (UNECE 2000).

Temperate forests exhibit a high diversity of deciduous broadleaf trees and evergreen species, many of which can attain impressive dimensions. Tree heights of 50 m have been documented for firs, Douglas firs, oaks and beeches, even in regions like Germany. Economically important species include oaks, beeches, maples, basswood, poplars, cherries, hickories and tulip trees. Conifers, including spruce, fir, and pine, play an important economic role locally as planted forests. Ecologically, temperate forests are not only rich in tree species but also in distinct shrub and herbaceous flora. Geophytes are a typical feature of temperate forests. Two structural layers can often be distinguished. Temperate forests are not homogenous but display a high diversity of tree types depending on local site and microclimatic conditions (Arbeitsgemeinschaft Forsteinrichtung 1985). Another important difference between boreal and temperate forests is the prevailing soil types. Temperate forests mainly grow on young, post-glacial soils, often brown soils. Eco-



Fig. 8.3 Large, homogenous tracts of pine forests interspersed with species such as aspen are a typical feature of the boreal forest (left); fire plays a considerable role in nutrient cycling and forest regeneration (right). (© Gerhard Langenberger)

nomically, temperate forests are still important providers of pulp wood, and especially construction timber. The production of maple syrup in eastern North America and of honey in fir forests ('Tannenhonig') can also be mentioned as specialised uses of temperate forests.

The coastal temperate rainforests of the North American west coast represent a unique subset of temperate forests, spanning from Alaska down to California along the Pacific coast and its mountainous regions. These forests are characterised by mild winters, moderate summers, and high precipitation levels. Dominated by conifers, they host some of the world's most remarkable tree species including redwood (*Sequoia sempervirens*) (◘ Fig. 8.4), Sitka spruce (*Picea sitchensis*), western red cedar (*Thuya plicata*), western hemlock (*Tsuga heterophylla*), and Douglas fir (*Pseudotsuga menziesii*). These forests are of considerable economic importance for the timber industry and are intensively exploited. Many of these species have been trialled as exotics in Germany; however, only Douglas fir has become a common component of German forests, where it now holds a considerable economic importance.

Mediterranean Forests

Mediterranean forests are defined by specific climatic conditions rather than the geographic locality, occurring not only around the Mediterranean Sea but also in regions such as South Africa, California, central Chile and Southern Australia. The respective climate is characterised by mild, rainy winters and very hot, dry summers. The vegetation is predominately sclerophylous with evergreen trees. Although the forests around the Mediterranean Sea were significantly degraded centuries ago, they continue to produce economically important forest products. The olive tree (*Olea europea*) provides fruits, oil and is also regarded as a popular timber source, while the cork oak (*Quercus suber*) produces cork, used for wine bottles stoppers and as a very good flooring material, and is formally classified as a forest species by the FAO (2020a). The pine *Pinus pinea* produces pine nuts (pignoli nuts), or pine seeds, used in modern cuisines like pestos. The Argan tree (*Argania spinosa*) of Morocco has recently attracted attention through its oil, which is traded as Argan oil and used in cosmetics but also as a food oil. Historically, the Lebanon cedar (*Cedrus libani*), mentioned in the Old



◘ **Fig. 8.4** Redwood (*Sequoia sempervirens*) in a Californian national park (note the relative height of the human), and the common clear-cutting practice of west-coast forests in Oregon. (© Gerhard Langenberger)

Testament, was a highly valued timber source in the Middle East. One of the most important plantation trees, the Monterey pine (*Pinus radiata*), originates from California, where it did not play a considerable role. However, it has proven to be a high potential plantation species outside its natural habitat (FAO and Plan Bleu 2018; FAO 2024).

Tropical Rainforests

Tropical rainforests are the world's most diverse forests. While the climatic conditions in these forests are more or less similar around the world, structure, species composition, and usability display distinct differences. Tropical rainforests are characterised by average temperatures between 24 °C and 30 °C, with a minimum annual average of 18 °C, and annual rainfall exceeding 1800 mm. They are dominated by a vast diversity of woody plants, reaching heights of 30–50 m, occasionally up to 70 m. Although species diversity is remarkably high, the density of individual species is generally very low, except in the dipterocarp forests of Southeast Asia. The high species diversity is also reflected in the structural diversity and associated ecological niches. A common misunderstanding is that tropical rainforests are impenetrable jungles. The opposite is the case, at least in undisturbed forests. Due to the shade created by the high and dense canopy, only little undergrowth develops, and it is easy to walk through the stands.

Three major tropical rainforests are usually distinguished: the American rainforest, mainly comprising the Amazon and Orinoco basins, the Indo-Malayan and Australian rainforest, and the African rainforest. All of them are considered important timber sources.

Mangroves

Mangroves (Fig. 8.5) are forests growing in the intertidal zone of tropical and subtropical coastlines, estuaries and deltas (cf. 'Sundarbans' in Bangladesh). Their adaptation to regular inundation by saltwater is unique, requiring tolerance to salinity as well as to oxygen shortage (cf. stilt roots, pneumatophores). Mangroves are found throughout the tropics and subtropics. Depending on the coastline and tidal dynamics, there can be a distinct zonation of species. Mangroves have been, and in some regions still are, a significant source of timber, firewood, charcoal, and tannins. They are important as food sources for fish and shells. With their zonation of different tree species, often extending a considerable distance into the sea, mangroves protect shorelines, play an important role in coastal



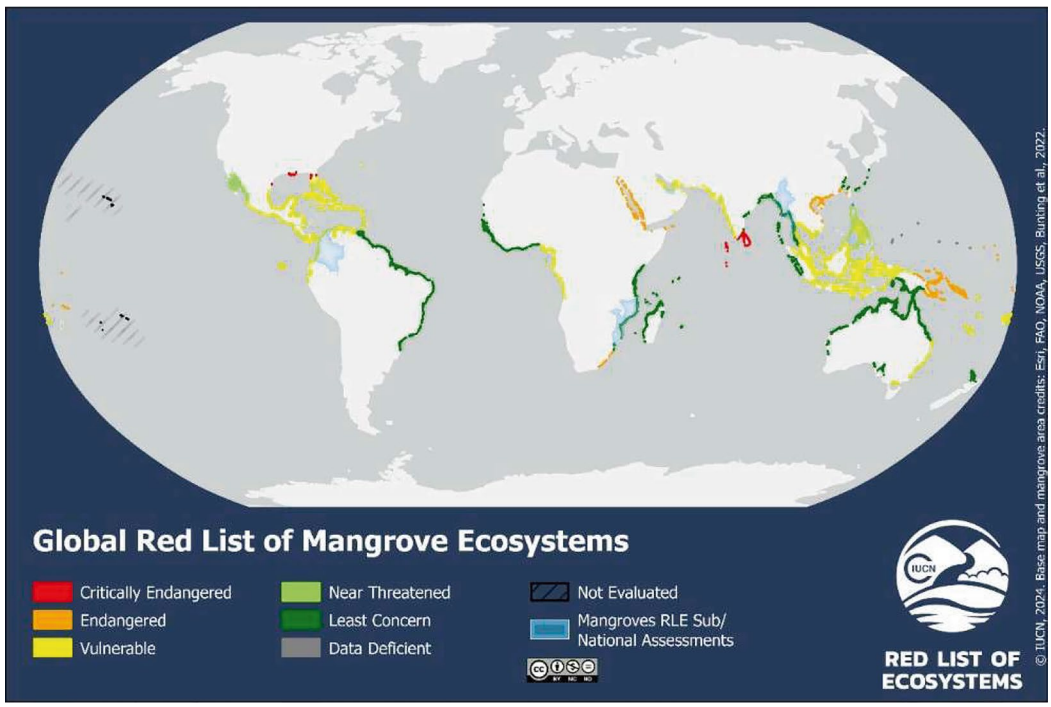
Fig. 8.5 Mangroves are an impressive feature of many tropical coastlines (Island of Leyte, Philippines). (© Gerhard Langenberger)

nutrient cycling, and serve as spawning grounds for fish, which shelter in shallow waters and within the dense stilt roots of species such as Rhizophora. However, heavy exploitation in the past has rendered many of these functions and services obsolete in some regions. Mangroves continue to be threatened by conversion into fishponds, rice fields, resorts and other uses (FAO 2023b) (see also: ◘ Fig. 8.6 and IUCN 2024) (◘ Table 8.3).

8.2.3 Natural and Planted Forests

Forests regenerate themselves naturally either through succession (cf. pioneer species) which often follows major disturbances such as fire or storms, and less obviously through the replacement of individual trees or tree groups in gaps (cf. climax forests) (cf. Excursus ► 8.1) caused by natural mortality or smaller disturbances, such as lightning or local storm damage. The same processes apply to human-caused disturbances, such as clear-cutting and selective logging. However, because the timing and direction of these natural processes are difficult to steer and manage, human intervention is often employed. Trees are usually replanted immediately after harvesting, a process called 'reforestation'. When a forest is re-established on land previously used for other purposes, such as crop production or cattle ranching, this is referred to as 'afforestation'.

Artificial regeneration can be carried out using either 'native' or 'exotic' species. Exotic species are those that are not native to the region or country. Thus, a native species in one country can become an exotic species in a neighbouring country and vice versa (cf. teak originating from Indo-Burma and nowadays being also planted in Central America, Eucalyptus from Australia planted in Spain, Monterey pine from California planted in New Zealand). The use of exotic species in forestry often sparks controversial and emotionally charged debates, unlike in agriculture, where it is widely accepted that all commercial crops are exotics. In Germany, an interesting case is the Douglas fir (*Pseudotsuga menzie-*



◘ **Fig. 8.6** State of mangrove ecosystems following red list. (© IUCN, 2024 licensed under CC-BY-NC-ND 4.0 (► https://creativecommons.org/licenses/by-nc-nd/4.0/))

Table 8.3 Different Forest types and their respective total biomass dry matter stock per hectare as well as average net primary production (cited in: Richter 2001)

Forest type	Dry matter stock per hectare / tons	Net primary production / g m^{-2} $year^{-1}$
Boreal forest	60–400	363–870
Temperate forest	150–500	1090–1775
Temperate pine forest, Oregon, USA	850	1890
Temperate redwood rainforest, California, USA	4525	380–650
Tropical rainforest	200–800 (1100)	3500
Mangroves		1700[a]

[a]Based on: Harishma et al. (2020)

sii), a high value timber species native to western North America. Douglas fir was native to Central Europe before the ice ages, but the glaciations caused the extinction of many tree taxa in Europe that can still be found in North America today. Douglas fir was successfully re-introduced to Germany at the beginning of the nineteenth century and has become an important source of construction timber. It has established itself well in forest ecosystems and can now be classified as naturalised. It is often used to replace Scots pine (*Pinus sylvestris*), which was planted to restore degraded soils in the past, since it is much more productive. Although Scots pine is 'native' to Germany, it naturally occurred only on a minority of the sites where it is now found. Many of these sites were originally occupied by broadleaf trees, particularly oaks. Thus, neither Douglas fir nor Scots pine are autochthonous (native) to these sites. Ecologically, it remains debatable whether Douglas fir is better suited than Scots pine.

Natural forests and planted forests are two distinct types of forest ecosystems, each with unique characteristics and roles in the environment and human use (FAO 2023a).

8.2.3.1 Natural Forests

These are forests that have developed naturally over time without direct human planting or intervention, although they may be influenced by activities such as selective logging. These forests often feature complex structures and diverse ecosystems, comprising a mix of tree species, ages and abundant wildlife and undergrowth. Natural forests may include primary forests (untouched forests, developed without significant human interference) and secondary forests (regenerated after disturbance). Natural forests are critical for providing habitats for a wide variety of plants and animals, conserving biodiversity, regulating the climate, storing carbon and maintaining water cycles and soil stability.

8.2.3.2 Planted Forests

These are forests that have been established through deliberate human intervention, such as planting seeds or saplings. They may be used for commercial production, or land reclamation. Planted forests often consist of a single or limited number of tree species (monocultures) and are typically designed for specific purposes, like timber production, erosion control or habitat restoration. Compared to natural forests, they may have simpler structures and less biodiversity. However, they can reduce pressure on natural forests by providing wood products and ecosystem services, including carbon sequestration, soil stabilisation and wildlife corridors, especially when managed sustainably.

Excursus 8.1: Pioneer and Climax Tree Species

Two major strategies of tree regeneration can be distinguished: Pioneer species (such as birches: *Betula* spp.) are adapted to establish on open, often disturbed sites. They require full sunlight, are generally fast growing, and thus especially suitable for the establishment of plantations. Pioneer species produce vast quantities of volatile seeds that are dispersed by wind and establish well on mineral soils. Climax tree species are adapted to regenerate in the microclimate of existing forests. They are shade-tolerant during their youth, grow more slowly and are more sensitive to climate extremes, such as drought and frost. Climax species typically produce far fewer but larger seeds. They can regenerate beneath mature pioneer species or in gaps within old forests. Typical examples are beech (*Fagus* spp.) and firs (*Abies* spp.).

8.3 Forest Ecosystem Services

Forests have accompanied human development from time immemorial, providing shelter, firewood, tools, construction materials, fruits, mushrooms and meat. While the provisioning of these services has remained consistent, the range and intensity of usage, the sophistication of products derived from forests, and the improved understanding of their ecological importance and contributions to human wellbeing have evolved significantly.

Forests have played a crucial role in human development due to a complex set of societal perceptions and expectations (cf. Harrison 1992). Today, beyond the sustainable production of physical goods, forests are expected to provide a multitude of services. This has resulted in restrictions in management practices that far exceed those of agricultural production, including tree species selection, mode of management, forest protection, application of agro-chemicals and even the mode of harvesting. This section gives an introduction into the modern usage of forests, distinguishing between their traditional role as physical resource providers and their contemporary role as non-physical service provider.

8.3.1 Forest Ecosystem Services

Forest ecosystem services refer to the broad range of benefits that forests provide to both humans and the environment. These services are essential for sustaining life, maintaining biodiversity, and supporting various economic activities (Masiero et al. 2019; Brander et al. 2023). They are typically classified into four main categories:

Provisioning Services

These are the tangible products or resources that forests provide, including:

- **Timber and Wood Products:** Used for construction, furniture, paper and fuel (firewood).
- **Non-timber Forest Products (NTFPs)**: Edible goods such as fruits, nuts, mushrooms, medicinal plants, as well as fibres, resins, rubber, dyes and more.
- **Fresh Water**: Forests help regulate the water cycle, ensuring the supply of clean water for consumption, agriculture and industry, while also supporting considerable freshwater biodiversity.

Regulating Services

Forests play a critical role in regulating environmental processes that benefit both ecosystems and human communities:

- **Carbon Sequestration**: Forests absorb and store carbon dioxide, helping mitigate climate change by acting as carbon sinks.
- **Climate Regulation**: By influencing local and global climates, forests help control temperatures, precipitation patterns and wind.
- **Air Quality Improvement**: Forests filter pollutants from the atmosphere, improving air quality.
- **Water Regulation and Purification**: Forests help regulate water flow, reduce flooding risks, and purify water by filtering out sediments and pollutants.
- **Soil Protection**: Forests prevent soil erosion by anchoring the soil with tree roots,

maintaining soil fertility, and protecting against landslides.

Supporting Services

These services are foundational to all other ecosystem services, providing the necessary conditions for ecosystems to function:

- **Nutrient Cycling**: Forests facilitate the cycling of nutrients, such as nitrogen and phosphorus, which are vital for plant growth and soil fertility.
- **Habitat Provision**: Forests are home to a vast array of biodiversity, including plants, animals, fungi, and microorganisms.
- **Soil Formation**: Forests contribute to the creation of healthy, rich soils through the decomposition of organic materials such as leaves and deadwood.

Cultural Services

Forests also have significant cultural, spiritual and recreational value for humans:

- **Recreation and Tourism**: Forests provide spaces for outdoor activities such as hiking, camping, birdwatching and ecotourism.
- **Spiritual and Aesthetic Value**: Forests hold cultural and spiritual significance for many communities and are appreciated for their natural beauty and inspiration.
- **Education and Research**: Forests serve as living laboratories, offering opportunities for scientific research, environmental education, and traditional ecological knowledge (Ndidzulafhi 2023).

Together, these ecosystem services provided by forests are vital for human well-being, economic development, and the overall health of the planet. They highlight the importance of conserving and managing forests sustainably to ensure that these benefits continue for future generations.

Excursus 8.2: Forests' Role as Long-Term Carbon Sink

Forests play a critical role as a long-term carbon sink, meaning they absorb carbon dioxide (CO_2) from the atmosphere, thus helping to mitigate climate change. The long-term carbon sink potential of forests is attributed to their ability to store large amounts of carbon in both the above-ground biomass (trunk, branches andleaves) and the below-ground biomass (roots). Additionally, forest soils contain significant amounts of carbon in the form of humus and soil organic carbon. Therefore, forest conservation, regeneration, and especially afforestation can contribute to the removal of CO_2 from the atmosphere and aid in to climate change mitigation. Nevertheless, forestry measures cannot fully compensate for excessive CO_2 emissions from the consumption of fossil fuels but can be an important component of a comprehensive strategy to reduce atmospheric CO_2 levels and mitigate climate change (Friedlingstein et al. 2024; IPCC 2022).

According to WRI (2022), global forests store approximately 861 gigatons of carbon, with 44% in soil (up to one-meter depth), 42% in living biomass (above- and belowground), 8% in dead wood, and 5% in litter. This is equivalent to nearly a century's worth of current annual fossil fuel emissions. While tropical rainforests make up only 30% of global tree cover, they hold 50% of the world's carbon stored in trees. Tropical forests store most of their carbon in living vegetation (biomass), whereas boreal forests store significant amounts in soils.

While forests play an important role as a long-term carbon sink, global CO_2 emissions from land-use, land-use change, and forestry (LULUCF) averaged 1.1 ± 0.7 GtC year^{-1} (4.1 ± 2.6 GtCO$_2$ year^{-1}) for the 2014–2023, period with a similar preliminary projection for 2024 of 1.1 ±0.7 GtC year^{-1} (4.2 ± 2.6 GtCO$_2$ year^{-1}). Since the late-1990s, emissions from LULUCF have shown a statistically significant decrease at a rate of around 0.2 GtC per decade. Emissions from deforestation, the main driver of global gross sources, remain high at approximately 1.7 GtC year^{-1} over the 2014–2023 period, highlighting the significant potential for emission reductions by halting deforestation. Sequestra-

tion of 1.2 GtC year^{-1} through reforestation, afforestation, and forestry offsets about two-thirds of deforestation emissions (Fig. 8.7). Additionally, smaller emissions result from other land use transitions, peat drainage and peat fire. The highest emitters during 2014–2023 in descending order were Brazil, Indonesia, and the Democratic Republic of the Congo, with these three countries contributing more than half of global land-use CO_2 emissions (Friedlingstein et al. 2024).

When forests are managed sustainably, they can continue to act as carbon sinks while providing resources like timber. Practices such as selective logging, replanting and minimising soil disturbance are vital for preserving the carbon balance. Conversely, deforestation and forest degradation release stored carbon into the atmosphere, exacerbating greenhouse gas emissions. Protecting and expanding forests is therefore essential to sustaining their function as long-term carbon sinks.



Fig. 8.7 Scenic forestry landscape, showcasing a vibrant mix of tall pine trees and colourful deciduous trees. (© Gerhard Langenberger)

8.3.2 The Protective Role of Forests

Forests play a vital role with significant economic value. In mountainous regions, they protect settlements, farms and infrastructure from avalanches and rockfalls (e.g. Scheidl et al. 2020). Forest climates help maintain air humidity, enhancing water infiltration rates and typically reducing surface runoff and erosion. Additionally, the root network of trees can stabilise soils and provide a buffer against landslides (Grima et al. 2020).

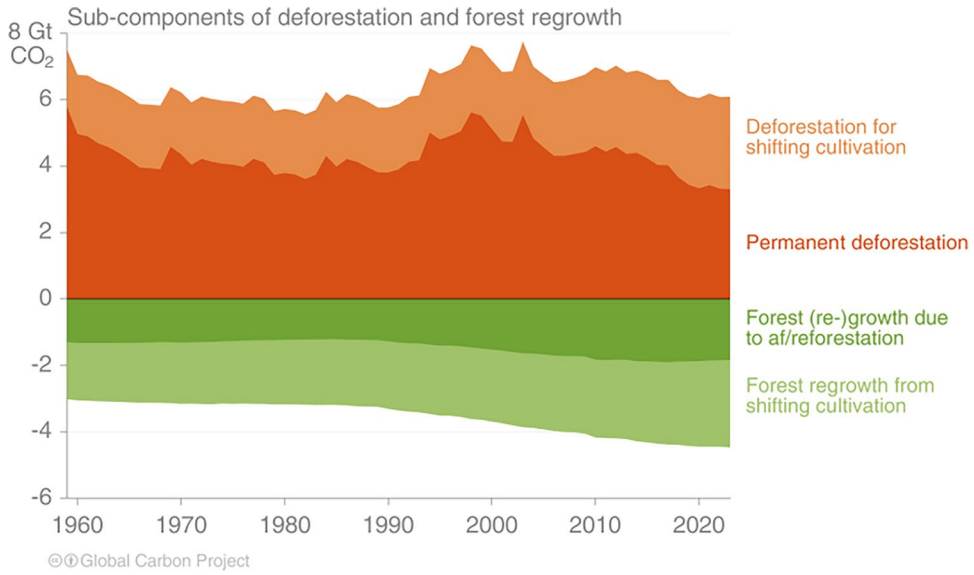
Along streams, forests stabilise riverbanks and often serve as water and sediment retention areas during floods. In tropical regions, mangroves protect shorelines, by serving as wave breaks and spawning ground for fish, thereby supporting the livelihoods of fishermen (e.g. Hubble et al. 2010; Riis et al. 2020).

Forests are also crucial for the hydrological cycle and serve as critical water protection areas (Ellison et al. 2017; EFI 2021). In urban centres, they play a considerable role as air filters and oxygen providers (Wilson et al. 2022). On a global scale, forests are crucial for carbon sequestration, serving as long-term carbon sinks (see also above: Excursus ► 8.2).

8.3.3 Forests for Recreational Activities

Forests are highly valued for recreational activities. In Germany, for example, people are said to have a strong connection to their forests. As a result, forests are open access, allowing individuals to enter without permission. Common activities include hiking, jogging, biking, mushroom collecting and hunting (see also ◘ Fig. 8.8). Forests also play an important role in leisure activities in many other countries around the world. Additionally, ecotourism deserves mention as it generates jobs and income in economically disadvantaged regions while contributing to the preservation of ecosystems (Esposito et al. 2020).

Ecotourism is seen as part of the so-called sustainable tourism sector. In the past, much was expected of ecotourism for developing countries and their rural populations. The basic idea was to protect ecosystems and biodiversity by providing alternative income sources



◘ **Fig. 8.8** Sub-components of deforestation and forest regrowht during 1960 to 2023; Annual emissions for the most recent period emissions from permanent deforestation declined over 2014–2023 but remain high at around 3.7 $GtCO_2$. Meanwhile, carbon dioxide removals through permanent afforestation/reforestation are 1.9 $GtCO_2$ per year over the same period (derived from Friedlingstein et al. 2024). (© Global Carbon Project, licensed under licensed under CC BY 4.0. (► https://creativecommons.org/licenses/by/4.0/))

for local communities, particularly in remote regions where livelihoods often depend on the use of the environment to survive. Accordingly, ecotourism can refer to a wide variety of ecosystems and activities, from diving the Great Barrier Reef to hiking to observe the last mountain gorillas on Mount Kilimanjaro. While initial expectations were high, they have not always been met, as developing the necessary infrastructure is complex and costly, often exceeding the revenue generated by visitor numbers. Furthermore, mass tourism within ecotourism can lead to ecological problems (e.g. Das and Jatterjee 2015; Brandt and Buckley 2018). Despite these issues, ecotourism has developed into a considerable branch of the tourism sector. In 2022, the global ecotourism market was valued at approximately USD 185.4 billion, with projections indicating growth to nearly USD 300 billion by 2026.

8.4 Forest Products

8.4.1 The Tree as Major Source of Forest Products

A tree is defined as an erect, lignified plant consisting of three major functional components: the root system, trunk and crown (Fig. 8.9). It

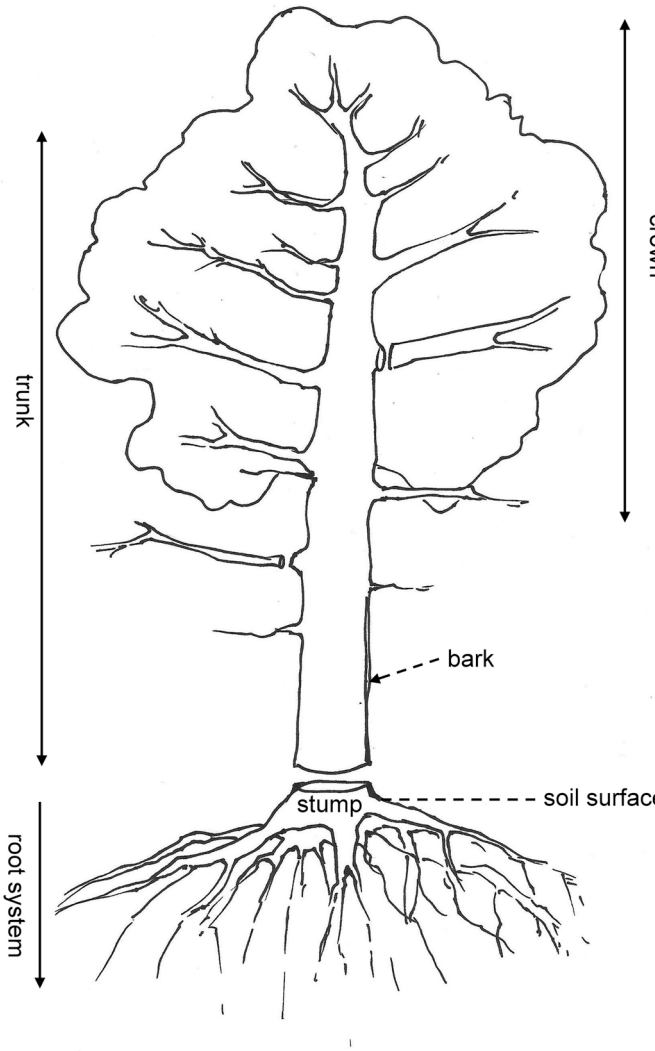


Fig. 8.9 The major components of a tree

includes both below-ground and an above-ground structures, which are critical for assessing biomass and carbon sequestration potential. The main tree parts that are used for economic purposes are the stem and major branches. Stumps, roots, minor branches and leaves usually remain in the forest to maintain organic matter and nutrient cycling, as most forests are not fertilised, unlike managed forest plantations.

The root system anchors and stabilises the tree in the soil. It ensures the provision of water and nutrients, usually supported by a symbiosis between the tree and fungi, known as 'mycorrhiza', which is specific to the tree species. The trunk merges via branches into the crown and connects the root system with the leaves, which serve as photosynthetic units. The trunk's central, woody part, the xylem, transports water and nutrients absorbed by the root system upward to the leaves via the branches. Conversely, the phloem, located on the inner side of the bark, transports the assimilates produced by the leaves downwards. These assimilates are used for tree growth, including root growth and regeneration, and to provide food for the mycorrhiza. The tree crown usually begins where the trunk starts to divide into a hierarchy of branches, at the ends of which the leaves are found. However, this structure varies based on the tree's age and position within a population. While the crown of young trees reaches down to the soil, old trees often have a long, straight bole without any branches, especially in dense forests. Solitary trees, in contrast, can retain their lower branches throughout their life. The root system of a tree must be adaptable to various soil conditions and is often species-specific. Three primary types of root systems can be identified: the taproot system, the heart root system, and the sinker root system (Fig. 8.10).

The taproot system consists of a central, dominant root accompanied by lateral roots. This system provides very stable anchorage and is typical for oaks, firs and pines, but also the neotropical rubber tree (*Hevea brasiliensis*). The heart-root system does not have a clear root hierarchy, but rather spreads homogenously in the soil. This configuration is common in a wide variety of species, such as birches and beeches. The sinker root system is characterised by a dominant horizontal root system near the soil surface from which vertical sinker roots grow to considerable depths. Since the sinker roots are sensitive to waterlogged and compacted soils, they are often not well developed, erroneously leading to the perception that the root system is generally flat. Spruce trees display a typical sinker root system.

8.4.1.1 Wood

The major physical resource provided by a tree is its wood. The ability to make fire, powered by wood, significantly impacted human

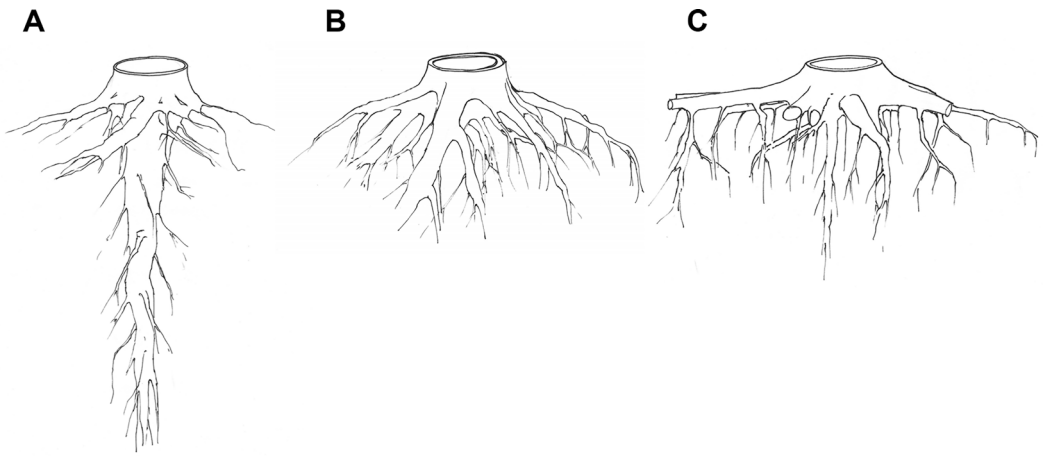


Fig. 8.10 The major root systems of trees: taproot system (left), heart root system (middle) and sinker root system (right). The actual development and structure depend strongly on site and soil conditions. Soils with a high-water table can lead to a very shallow and flat root system (even in pines)

evolution and remained the dominant energy source for hundreds of thousands of years, until coal and oil eventually took its place. In the wake of the recent renewable energy boom, wood is currently experiencing a renaissance as an energy source, either in its raw form, as wood chips, or pellets (Fig. 8.13). In addition to energy production, wood serves as raw material for tools, furniture, various construction purposes and paper.

To understand the relevance of wood in a bioeconomy, it is crucial to be aware of its composition and features. The primary components of wood are cellulose, hemicelluloses and lignin. Wood is often compared to a concrete construction, with the cellulose fibres representing the steel reinforcement which give the construction elasticity, and the lignin representing the concrete which provides stability. Additionally, wood contains fat, starch and sugars as minor components, as well as resins, tannin agents, colour agents, etc. Chemically wood is composed of carbon (C) (50%), oxygen (O) (43%), hydrogen (H) (6%), nitrogen (N) and minerals (1%).

Since the molecular weight ratio of carbon dioxide to carbon is 3.7 to 1, the carbon sequestration potential of wood can be calculated based on its species-specific dry weight. It is important to note the traditional distinction between hardwoods (broadleaved trees) and softwoods (conifers). Hardwoods are usually heavier and have a shorter fibre length compared to softwoods, which is particularly relevant in paper production. Table 8.4 shows the average dry weight and bulk density of common timber species. Bulk density refers to the mass of dry matter relative to the volume of freshly harvested wood and is a crucial parameter for calculating, among other things, the carbon dioxide equivalents (CO_{2equ}) stored in trees.

Excursus 8.3: Calculation of carbon dioxide equivalents (CO_{2equ}) stored in trees

For example, a balsa tree with a volume of 1 m^3 has a dry matter wood content of about 120 kg. As the proportion of carbon is 50%, this equates to 60 kg of carbon. Given that the molecular weight of carbon dioxide (CO_2) is 3.7 times that of carbon, 1 m^3 of balsa wood stores 60 kg × 3.7 = 222 kg of CO_2. Similarly for a beech tree with a bulk density of 554 kg/m^3, the stored carbon dioxide equals 1025 kg, and for a pockwood tree, it amounts to 1935 kg.

Dry wood has a calorific value of 5–5.2 kWh/kg, and depending on the species and its wood density, one m^3 of piled hardwood can replace around 200 litres of fuel oil given a wood moisture of about 15% (air dry).

8.4.2 Forest Product Pathways

Wood's unique chemical and physical properties set it apart from other materials, allowing a wide range of applications. It is lightweight, flexible, easy to work with, and often highly ornamental. These characteristics make wood ideal for construction purposes, including houses and boats, as well as for flooring, furniture carvings, tools, and the production of paper and semi-natural fibres like viscose and modal. Wood also serves food industry applications, for example, as artificial vanillin produced from lignin and as xylose, a sugar produced from wood. Fig. 8.11 provides an overview of the typical pathways of forest product utilisation.

Table 8.4 Wood density figures of some common tree species (all data from: Knigge and Schulz, 1966)

Tree species	Average dry density in g/cm³[a]	Boundary values of dry density in g/cm³[a]	Bulk density in kg/m³[a]
Balsa	0.13	0.07–0.23	120.8
Spruce	0.43	0.37–0.54	377.1
Poplar	0.37	0.27–0.65	376.8
Pine	0.49	0.30–0.86	430.7
Maple	0.59	0.48–0.75	522.2
Oak	0.64	0.38–0.90	561.1
Beech	0.66	0.54–0.84	554.3
Pockwood	1.23	1.20–1.32	1045.5

[a] There is a small but relevant difference between the dry density, usually measured in g/cm³, and bulk density, measured in kg/m³. This is due to the fact that wood shrinks during the drying process. The bulk density relates the fresh volume of a wood sample or tree to the respective wood content. The dry density relates the volume of an oven-dried, shrunken wood sample to its weight. The latter figure is therefore higher, since the reference volume is smaller

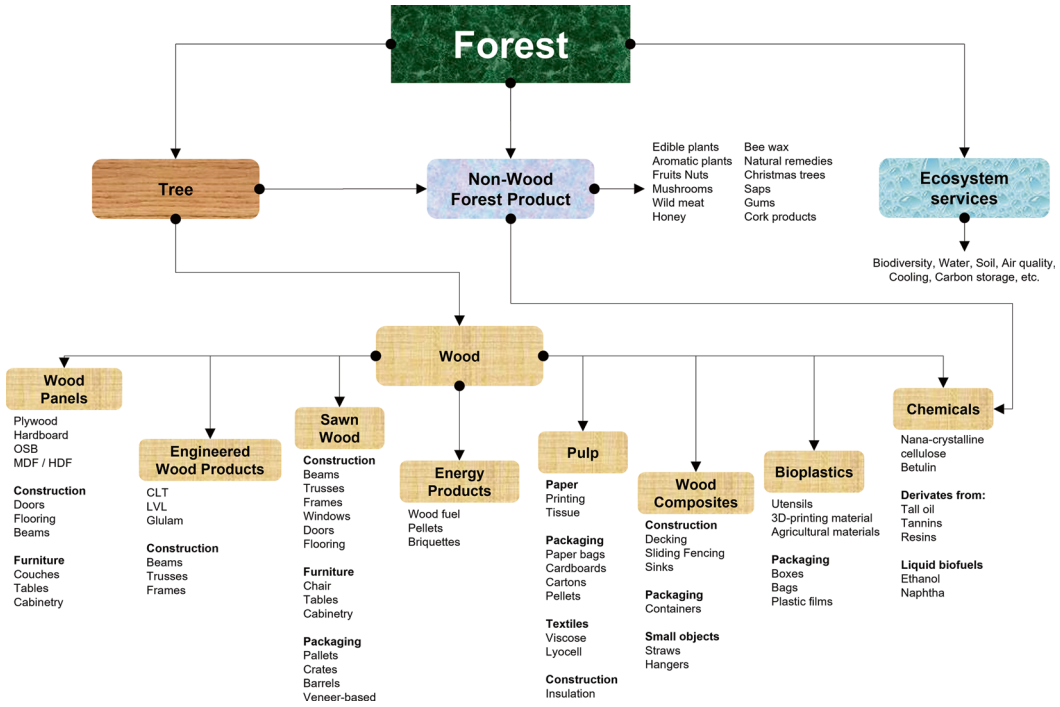


Fig. 8.11 Typical pathways of forest product utilisation. (Adapted from Verkerk et al. (2022))

8.4.2.1 Pulp and Paper

Pulp and Paper refers to the industry and processes involved in transforming raw plant fibres such as those from wood, recycled paper or other plant materials like bamboo, hemp and cotton, into pulp, which is then used to produce various types of paper products. Pulp is produced through mechanical, chemical or semi-chemical processes that break down raw materials into fibres (see Sect. ▶ 17.2.3 for processes in a pulp mill). It can be further processed to produce different grades of paper and is also used in products like tissue, cardboard and specialty papers. Paper itself is a thin sheet material formed by pressing together moist fibres (usually derived from pulp) and drying them into flexible sheets. Paper serves a wide range of applications, including writing, printing, packaging and industrial uses. Its thickness, texture, and strength can vary depending on the production method.

8.4.2.2 Construction Wood

Construction wood, often called lumber or timber, refers to wood that has been processed for building and structural applications. It includes various types and shapes of wood specifically cut and treated for use in construction and is a widely used building material.

Typically, construction wood is sourced from softwoods such as pine, spruce and fir, valued for their strength-to-weight ratio and ease of handling. Hardwoods like oak and maple may also be used, especially when higher durability or specific aesthetic properties are desired. It is commonly used for structural framing (like beams, joists and studs), flooring, decking and various other building components. Hardwoods are also essential for residential, commercial and industrial construction projects. To improve its durability, construction wood is often treated to resist decay, insects and moisture. Additionally, grading ensures that lumber meets specific strength and quality standards essential for safe construction (◘ Fig. 8.12)

8.4.2.3 Cellulosic Fibres for Textiles

Wood pulp has been used for more than a century in the production of viscose for the textile industry. The three main types of regenerated cellulose fibre are viscose, acetate and lyocell. While wood pulp remains the pri-



◘ **Fig. 8.12** Lumber yard storing cut boards for construction purposes. (© Gerhard Langenberger)



Fig. 8.13 Wood stored for charcoal making in Copperbelt province, Zambia. (© Melvin Lippe)

mary cellulose feedstock for producing regenerated cellulose fibres, other cellulose sources, such as bamboo, bast fibres, cotton linters and sugarcane bagasse, are increasingly being used as feedstock as well (Verkerk et al. 2022).

8.4.2.4 Resins and their Chemical Derivates

Tree resins are one type of non-wood forest products (NWFP) and have been used for many centuries in various applications. These include their use as waterproofing agents for coating ropes and tarps or being processed into tar or pitch for sealing wooden ships (Verkerk et al. 2022).

Resin-derived chemical compounds are widely used in the chemical and food industries as raw materials for products such as disinfectants, detergents, paints, adhesives and flavourings. While many tree species produce resin, the majority of commercially available natural resins are derived from pine trees. These compounds, commonly referred to in the industry as pine chemicals, are obtained through various extraction methods. The primary method involves tapping resin (or oleoresin) from live, standing trees. Another approach involves extracting chemical compounds from old tree stumps by grinding them into smaller pieces using solvents. Resin is typically separated into two intermediate products: a volatile fraction known as turpentine and a solid fraction called rosin (also known as colophony).

Turpentine and colophony can also be produced through a process linked to the pulping industry (see also Fig. 8.14). This involves distilling crude tall oil — a by-product of the kraft pulping process—into tall oil rosin and other chemicals. Additionally, the kraft pulping process generates crude sulfate turpentine as a significant by-product. These pine chemical derivatives can be further refined into a wide variety of chemicals, serving as essential raw materials for various industries (Verkerk et al. 2022).

8.4.2.5 Bioplastics

Bioplastics derived from wood are biodegradable or bio-based plastics made wholly or partially from wood components such as cellulose, lignin or hemicellulose. Unlike conventional plastics, which are typically made from petroleum-based materials, these bioplastics are designed to reduce reliance on fossil fuels, decrease carbon emissions, and enhance environmental sustainability. These renewable alternatives to conventional plastics offer eco-friendlier options for packaging, consumer

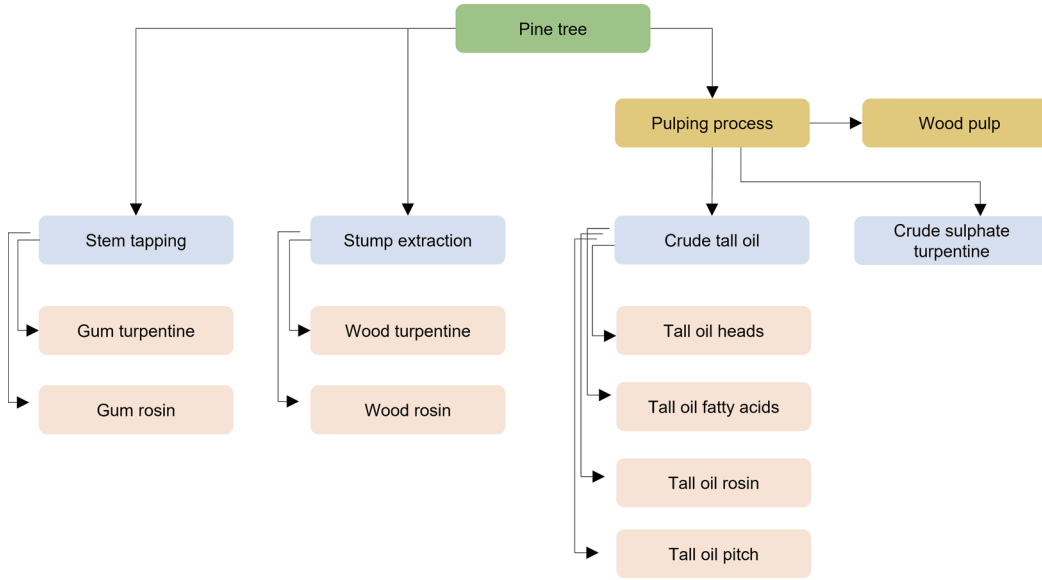


Fig. 8.14 Simplified pine chemical product pathways. (Adapted from Verkerk et al. (2022))

products, and various other applications, contributing to the shift toward a circular bioeconomy (Verkerk et al. 2022).

8.4.2.6 Engineered Wood Products (EWP)

EWPs are a category of wood-based materials manufactured by binding or fixing the strands, particles, fibres, or veneers of wood with adhesives or other bonding methods to form a composite material. These products are designed to maximise the strength, stability, and utility of wood for various structural and non-structural applications. They provide versatility, resource efficiency and reliability, making them a popular choice in modern construction, furniture making and various other industries (Verkerk et al. 2022).

Common Types of Engineered Wood Products include:

- Plywood: Made by gluing together thin layers (veneers) of wood with grains running at right angles, providing strength and resistance to splitting.
- Oriented Strand Board (OSB): Composed of compressed wood strands and adhesives, OSB is widely used in construction for sheathing and flooring.
- Laminated Veneer Lumber (LVL): Produced by bonding thin layers of wood veneers, LVL is commonly used for structural beams and headers.
- Glue-Laminated Timber (Glulam): Made by gluing together layers of solid wood, glulam beams are used for structural applications requiring high strength and long spans.
- Cross-Laminated Timber (CLT): Formed by stacking and gluing layers of wood panels at right angles, CLT provides exceptional strength and is used in large-scale construction projects.
- Medium-Density Fibreboard (MDF) and Particleboard: These products are made from wood fibers or particles bonded together under heat and pressure, often used for furniture, cabinetry, and interior applications.

8.4.2.7 Global Production of Forest Products

Globally traded forest products are documented in a standardised format. Table 8.5 presents the primary trade categories and their associated volumes for 2022.

Table 8.5 Global production of major forest products in 2022 (FAOSTAT 2024)

Product[a]	Unit	Production in 2022
Roundwood	million m^3	3.983
Wood fuel	million m^3	1.967
Industrial roundwood	million m^3	2.016
Sawlogs and veneer logs	million m^3	1.142
Sawn wood	million m^3	481
Wood-based panels	million m^3	375
Woodchips and particles	million m^3	269
Wood residues	million m^3	243
Paper and paperboard	million tonnes	414
Wood pulp	million tonnes	196
Pulp for paper	million tonnes	199
Fibreboard	million m^3	118
Wood pellets, briquettes and other agglomerates	million tonnes	54

[a] For definitions, see FAO (2023b)

8.4.3 Non-wood Forest Products (NWFP)

Other physical goods that can be obtained from forests are referred to either as 'non-wood' or 'non-timber forest products' (NWFPs or NTFPs). NWFPs include berries, mushrooms, aromatic and decorative plant material, saps, resins, nuts, honey and game. According to the FAO (2020a, b), these products represented an economic value of USD 7.7 billion in 2015, mostly comprising edible plants (37 %), ornamental plants (22 %), wild meat (9 %), other plant products (8 %), honey and beeswax (7 %), and medicinal and aromatic plants (5 %) (Verkerk et al. 2022)

Depending on the region of the globe, NWFPs may play a significant role in the livelihoods of local populations or be used for recreational purposes. For instance, cork from Mediterranean cork oak stands, categorised as forests, is classified as a non-wood forest product, as is the natural rubber produced in the millions of hectares of rubber tree plantations in Southeast Asia.

A special case with considerable regional importance is the meat provisioning service. So-called 'bushmeat' is an important source of protein in many tropical regions (Reinhardt Nielsen et al. 2017; Silva et al. 2023). In some Southeast Asian countries, such as Vietnam, forest species are being hunted to extinction to feed the insatiable hunger for exotic meat among the region's emerging affluent population (Nguyen and Jones 2022). Bushmeat hunting and trade is usually illegal and uncontrolled and has considerable negative impacts on the affected species' populations. However, hunting practices in North America and Europe, for example, show that it is also possible to use forests as a sustainable source of considerable amounts of meat. Table 8.6 shows the case of Germany, where nearly 436.000 persons owned a hunting licence in 2023 (DJV 2024).

In addition to the monetary value of the meat, annual hunting fees can constitute a considerable source of income for forest owners, often exceeding the annual income from wood production. Another economi-

Table 8.6 Bushmeat provision of forests and agricultural land together[a] in Germany, hunting year 2022/23 (only hoofed game) (DJV 2024)

	Amount in tonnes[b]	Value in mio €[c]
Red deer	4574	20.581
Fallow deer	2098	10.491
Wild boar	19572	78.290
Roe deer	13554	67.770
Total	39798	177.132

[a] Hunting districts are not defined by land-use boundaries but rather by ownership. The total hunting area in Germany covers 32 million hectares
[b] Animal with skin and bones
[c] Price for whole animal with skin and bones ('primary value'). The monetary value given in the table does not take into account the associated value chain and added values due to processing.



Mushroom *Boletus edulis*



Bushmeat frogs



Bushmeat *Cervus mariannus*

Fig. 8.15 Examples of non-wood products. (© Gerhard Langenberger)

cally important factor is the general expenditures by hunters on hunting equipment and related items, which in 2023 amounted to a notable 2.7 billion Euros in Germany (DJV 2024).

A particularly controversial and often emotionally debated form of hunting is trophy hunting—especially in Africa—regarding its socio-economic and environmental benefits or impacts (cf. Traill et al. 2024) (Fig. 8.15).

8.5 Forest Management

The management of forests has some peculiarities that must be understood to properly assess their potentials and limitations in a bioeconomy. One major difference compared to all other biological production systems is the time horizon. In forestry, we are dealing with decades or even centuries—in contrast to the short rotation time of modern agriculture. This requires much more foresight. In

agriculture, a poor decision might result in the loss of an annual crop. In forestry, however, a wrong decision regarding tree species may reveal its disastrous consequences only after decades. For example, a single exceptional summer or winter season can devastate an entire long-term investment in one blow. This long-term perspective together with the necessity of food production, is the main reason forests in many developed countries have been pushed back into less productive or difficult-to-manage sites and replaced by agriculture, especially on good soils. Similar developments can be observed in the global South, where most of the deforestation is caused by the conversion into agricultural land.

As a result, forest investments typically concentrate on short-rotation plantations, while the management of natural or near-natural forests is carried out in state-owned or traditionally privately-owned forests, often with a long and intergenerational perspective.

8.5.1 The Exploitation and Use of Forests

The initial use of forests was exploitative, with desired products such as meat, wood, and other non-wood products being harvested without regard for regeneration. Over time, people realised that overuse could lead to a shortage of supply. Consequently, many indigenous communities worldwide established usage restrictions. While these restrictions are often unwritten and undocumented, they are typically reflected in societal norms or religious practices (Sinthumule 2023).

However, forests were often cleared to create open space for crop production. This form of agriculture can still be found in some world regions, where it is referred to as 'shifting cultivation' or 'swidden agriculture' (Ellis et al. 2010). The use of fire is a key element in this practice, and over time, vast areas can be deforested, even with very simple tools. Forests are cut down during the dry season and the dry matter is burned at the beginning of the rainy season. The open land is then used for crop production for two to three years. After that period, it is abandoned, allowing the forest to re-establish and regenerate into a secondary forest (Heinimann et al. 2017; Nair et al. 2021).

The great reduction in tropical forests and boreal forests originates from technical developments, especially the chainsaw and related heavy machinery such as bulldozers, skidders, and modern harvesters. With these tools, it became and remains possible to extract timber at an unprecedented speed. Although typically only the most valuable trees are harvested, the damage to the remaining forest can be susbstantial, due to the heavy machinery and the lack of technical (felling) skills. Additionally, lack of regulations, non-implementation of existing rules, and corruption (Transparency International 2019) have contributed to the degradation and disappearance of large areas of tropical forests.

In contrast, in sustainable forestry, two major approaches can be distinguished: *clear felling* and *selective logging*, the latter one involving the removal of individual trees.

Clear felling is the most simple and straightforward practice where all trees in a given area are harvested. From a production perspective, this method offers considerable advantages. Harvesting can be carried out efficiently, providing a large amount of biomass. Clear felling also allows for site modifications such as stump extraction and ploughing which requires large machinery, and facilitates artificial regeneration. This type of forest usage and regeneration is typical in plantation forestry (cf. *Eucalyptus, Acacia, Pinus* spp.), where the primary objective is the rapid production of a single commodity.

Selective logging targets individual trees of high value, aiming to preserve forest structure and functions. It is often practiced in mixed, near-natural forests. One selection criterion is a preset minimum diameter. This management practice is highly demanding and involves all aspects of management. First, the forest manager must carefully identify the right trees, and harvesting logistics need to be worked out before logging begins to reduce the impact on the remaining forest stand. This requires the establishment of a skidding infrastructure and related felling schemes (cf.



8

Fig. 8.16 Clear-felling system in conifer forests of the western United States. (© Gerhard Langenberger)

directed felling). Skilled logging is essential to follow the felling scheme and minimise felling damages. The objective is to promote the growth of high-value individual trees, while allowing natural regeneration to occur concurrently.

However, in practice, the situation is much more complex and diverse than described above, and the two approaches are often mixed, depending on local circumstances. For example, small clear-cuts can be used to promote light-demanding species, and natural regeneration is sometimes assisted by artificial planting to support stagnant regeneration or alter species composition. Figure 8.16 illustrates the common clear-felling practice in conifer forests in the western United States, where large tracts of forests are clear-cut but blocks of forest are maintained in between.

8.5.2 Forest Management

Generally, five natural development phases can be distinguished in the lifetime of a tree:

- Establishment phase: This involves the establishment of a tree seed at a given site.
- Youth phase: The time between the establishment and maturity (seed production) of a tree.
- Optimal phase: Adult stage with regeneration.
- Stagnation phase: Decreasing vitality.
- Natural decay: Die-off and replacement.

The length of each stage is species-specific and, as a result, different species are used in different management schemes. For all production forests, the stagnation phase and natural decay are eliminated by prior harvest.

Two major tree types can be distinguished based on their life strategy: the *pioneer species* and the *late successional* and *climax forest* species (see also: Excursus ▶ 8.1). Typical *pioneer species*, such as birch and pine, all share a similar strategy. They produce large quantities of wind-dispersed seeds, prefer mineral soils for regeneration and require full sunlight to establish and grow. Plantation forestry uses species from this group, as they show tremen-

dous growth in their youth but soon reach a peak growth rate, allowing for short rotations. Their natural lifespan is usually but not always (cf. *Eucalyptus camaldulensis*) comparatively low (Table 8.7).

Most *late successional and climax forest species* are adapted to regenerate within the forest, in shady conditions or small light gaps. The seeds are usually larger (e.g. beech) than those of pioneers, and the seedlings often cannot tolerate full sunlight exposure or temperature extremes. The establishment of these species in open spaces poses considerable challenges. Therefore, such species are more often used in permanent mixed forests. They typically grow more slowly in their youth than pioneer species but maintain a considerable level of growth into old age and can live for quite a long time (Table 8.7).

Once trees have been established, either as a monoculture or as part of a natural regeneration concept, they need to be managed. Fertilisation is common practice in forest plantations. The risk of fire should be considered in plantation schemes, as well as competition from grass, which may necessitate weeding. Lianas are often reported as a serious problem hampering natural regeneration in selectively logged forests in the tropics. In these cases, growth regulation and competition control are essential after the young trees have been established. For example, misshapen, damaged, or low-vitality trees may need to be removed. As the trees grow taller and start to differentiate, thinning is required. This involves promoting trees which fulfil quality and growth expectations by removing competitors. Thinning is the first management

Table 8.7 Life expectancy of selected tree species and production figures[a]

Tree species	Potential max. age in years	Average rotation period in years	Average annual increment[b] in m^3 /ha
Broadleaf trees			
Alder (*Alnus glutinosa*)	150	90	4.5–8
Ash (*Fraxinus excelsior*)	200	120	4.5–6.1
Beech (*Fagus sylvatica*)	300	150	4.2–8.6
Birch (*Betula pendula*)	120	80	3.6–4.9
Eucalyptus (*E. Camaldulensis*) (plantation)	1000	7–15	2–30
Oaks (*Quercus petraea, robur*)	800	200	3.6–6.4
Teak (*Tectona grandis*)	>200	80	0.6–14.8
Conifers			
Douglas fir (*Pseudotsuga menziesii*)	1000	100	9.4–17.1
Fir (*Abies alba*)	500	150	7–12.8
Larch (*Larix decidua*)	500	140	4.1–7.2
Pine (*Pinus sylvestris*)	600	140	1.2–7.0
Spruce (*Picea abies*)	600	120	5.6–11.9

[a]Different sources: Schütt et al. 1992; Schober 1987; Lamprecht 1989; Jacobs 1955; [b]The annual increment strongly depends on site quality and thinning strategy; the values given for temperate-zone species refer to the highest rotation length given in yield tables. If rotation length is reduced, average annual increments can be higher

step which can lead to positive economic returns through the sale of wood. Depending on the management scheme, several thinning rounds may be necessary before the final harvest.

8.5.3 Deforestation and Forest Degradation

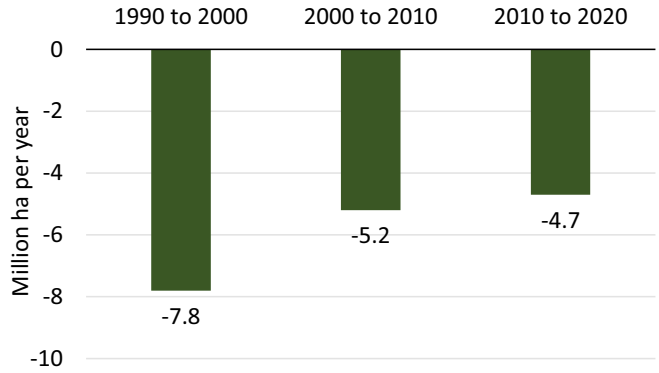
Deforestation and forest degradation are global environmental issues with sifnificant consequences for ecosystem services, biodiversity, and the wellbeing of forest dependent people and societies (FAO 2020a; IPCC 2022). These issues can result from human activities, such as farming or logging, or from natural disasters, including storms, wildfires or pest outbreaks, among others (Archard and Hansen 2016; Thompson et al. 2013).

Although the importance of forests is undisputed, the annual loss of forested areas between 2010 and 2020 still amounted to 4.7 million hectares per year. Deforestation hotspots are especially prevalent in Southeast Asia, Sub-Saharan Africa and South America (◘ Fig. 8.17). While this figure represents a 40% decrease compared to the period of 1990 to 2000, it still reflects the loss of forest area each year comparable to the size of Switzerland (4.1 million hectares) or Slovakia (4.9 million hectares).

Most tropical deforestation takes place in areas where agriculture serves as the primary driver of forest loss (◘ Fig. 8.19). Some of this deforestation is driven by both domestic and export demands for agricultural products. However, agriculture-related deforestation can also happen without expanding managed agricultural land. This can occur through several mechanisms, sometimes leading to abandoned or semi-abandoned deforested areas (Pendrill et al. 2022; ◘ Figure 8.18). In contrast, the North does not experience net deforestation, but centuries-old boreal and temperate old-growth forests continue to be cleared, either legally or also illegally in some cases (FAO 2020a).

While deforestation refers to the permanent loss of forest cover, such as through conversion into agricultural land or housing areas, degradation pertains to the alteration of a forest's integrity. Degradation affects its structure, species composition, and ecosystem functions and is often a precursor of deforestation. The global area of degraded tropical forests is currently estimated at a minimum of 500 million hectares, potentially exceeding the combined deforestation hotspots in the Amazon, Congo Basin and Indonesia (Vancutsem et al. 2021).

In response, the European Union recently issued the regulation of deforestation-free products (▶ EUDR), requiring supply chain actors to ensure that the sourcing, production, and distribution of goods and materials originating from cacao, cattle, coffee, oil palm, soy, rubber, and timber imported into the EU-27 occur without contributing to deforestation or the degradation of natural forests.



◘ **Fig. 8.17** Global annual forest area change (per decade) during the period of 1990 to 2020. (Based on FAO (2020a))

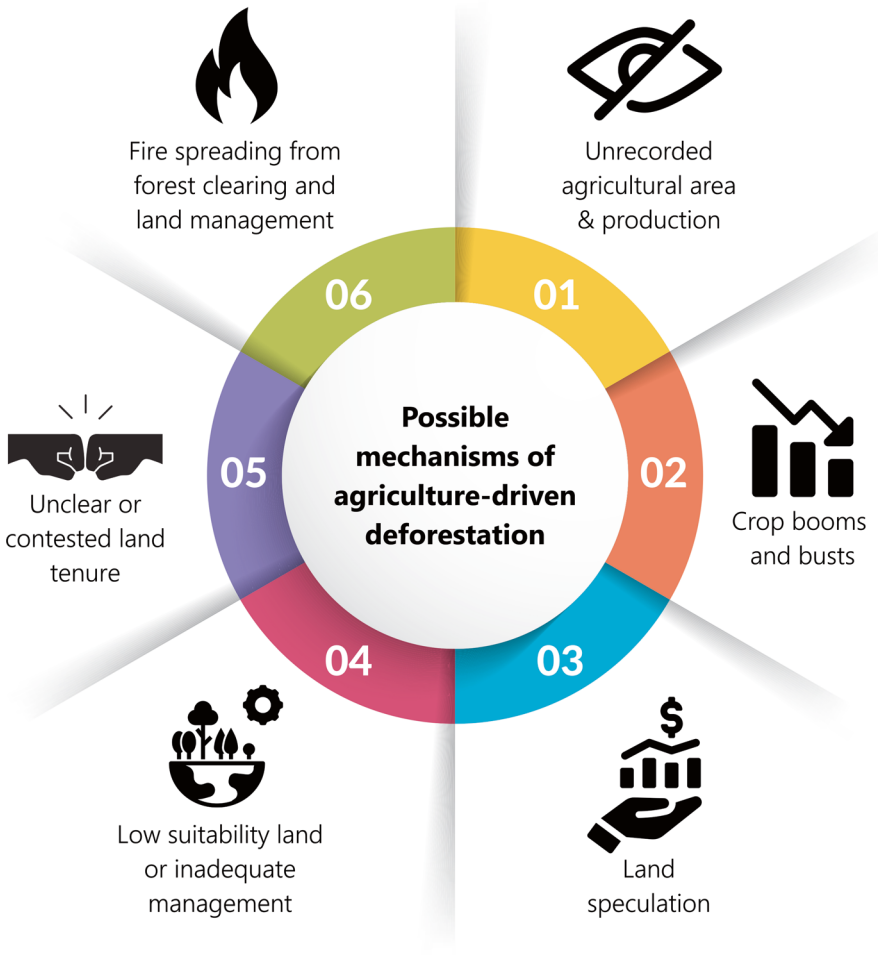


Fig. 8.18 Possible mechanisms of agriculture-driven deforestation. (Based on Pendrill et al. (2022))

This approach aims to ensure deforestation-free products while preserving forest ecosystems, promoting sustainable land use, and reducing greenhouse gas emissions associated with forest loss. You may watch a short explanation movie on deforestation-free supply chains on the website of the ▶ Global Landscapes Forum.

8.5.4 Reforestation, Afforestation and Forest Restoration

Reforestation, afforestation, and forest restoration are important processes aimed at increasing forest cover, improving environmental quality and supporting biodiversity.

- **Reforestation:**
This involves the replanting or natural regeneration of trees in areas where forests have been recently lost or depleted, usually due to activities such as logging, agriculture, or fires. The goal is to restore tree cover, improve soil quality, preserve biodiversity, and sequester carbon. Reforestation may involve planting the same species that were previously present or a mix of species to create more diverse and resilient forests.

- **Afforestation:**
Afforestation is the process of planting trees in areas that were not previously covered by forests. Unlike reforestation, which focuses on restoring previously forested areas, afforesta-



Fig. 8.19 Recently deforested forest site in the Ecuadorian Amazonas. (© Melvin Lippe)

tion transforms non-forested lands—such as pastures, barren land, or even deserts—into forests. This process can help combat climate change by sequestering carbon dioxide, reducing erosion, improving water cycles, and enhancing biodiversity.

Forest Restoration:

Forest restoration focuses on returning degraded or deforested lands (e.g. Fig. 8.20) to a more natural or productive state, aiming to restore the ecological functions, biodiversity, and health of a forest ecosystem. This process can involve reintroducing native tree species, improving soil and water conditions, and fostering wildlife habitats. Forest restoration goes beyond merely planting trees; it emphasises rebuilding a balanced and self-sustaining forest ecosystem that supports both biodiversity and human needs.

While reforestation, by definition, involves restoring forest cover to sites with previous forest cover, afforestation refers to establishing forests on sites without prior forest cover or those with long-term alternative uses, such as agriculture or pasture. Reforestation typically focuses on tree coverage to meet the forest definition and often involves tree planting. In contrast, restoration is more comprehensive, addressing both the structure and functions of the previous forest, with an emphasis on the ecosystem. A special case is the Assisted Natural Regeneration (ANR), a method of forest restoration that includes both direct and indirect measures (FAO 2020a).

Direct measures involve activities such as planting and sowing or assisted regeneration through Farmer-managed Natural Regeneration (FMNR). Indirect measures include improved land use and resource management practices, such as fire prevention, controlled grazing (e.g. fencing), and firewood usage, to support natural regeneration in designated areas. ANR is referred to as a cost-effective restoration method that enhances the productivity and ecosystem functions of degraded lands by facilitating natural successional processes. It involves interventions to overcome barriers to natural regeneration, such as soil degradation and competition with



Fig. 8.20 Deforested and degraded grassland areas in Northern Luzon, Philippines. (© Melvin Lippe)

weedy species. ANR is a growing field in restoration science with successful global applications, offering a range of interventions to achieve various restoration goals and policy objectives (FAO 2019).

8.6 Sustainability, Forest Certification Schemes and Sustainable Forest Management

Sustainability has become a ubiquitous buzzword, with as many meanings as it has advocates. The 'invention' of the term by von Carlowitz in 1713 originally aimed at ensuring a permanent timber source for industry. Since then, the meaning of the term has evolved, based on scientific progress and ecological understanding, and has now taken on an ecosystem-oriented connotation, encompassing the protection of species diversity and ecosystem functions.

While forest management regulations in temperate zone and industrialised countries are usually well developed and implemented, forest use in the tropics has historically been, and often still is, pure exploitative. This has lead to forest degradation and, ultimately, transformation, sometimes intentionally to expand agricultural land. In response to the tremendous forest losses in the tropics during the second half of the last century, environmentalists and other civil society organisations came together to explore options for changing this development through market pressure. As a result, **forest certification schemes** were developed, the most prominent of which is the ► Forest Stewardship Council (FSC). Initiated by environmental and human rights organisations (in particular WWF, Greenpeace, etc.), FSC was met with a response from forest owners and the forest industry, who created their own, more user-friendly certification scheme, the ► Programme for the Endorsement of Forest

Certification (PEFC). There are other certification schemes, each with somewhat different criteria and focus, such as that of the ► organic farming label 'Naturland'.

Sustainable Forest Management (SFM) is a comprehensive approach to managing and using forests in ways that preserve their biodiversity, productivity, regeneration capacity, vitality, and ability to fulfil ecological, economic and social functions. The goal of SFM is to ensure that the benefits provided by forests can meet the needs of present and future generations, while maintaining the health and integrity of forest ecosystems.

Key Principles of Sustainable Forest Management include environmental conservation, aimed at protecting habitats for wildlife and maintaining ecosystem services like water purification, carbon storage, and soil stability. It involves efforts to prevent deforestation, minimise forest degradation, and promote reforestation and afforestation. SFM further recognises the importance of forests to indigenous peoples, local communities, and others who rely on them for their livelihoods, cultural practices, and well-being. It emphasises participation, respect for indigenous rights, and equitable benefit-sharing in forest management. Ideally, SFM seeks to balance timber production and other economic activities with conservation and environmental protection to sustain long-term economic value.

Practices in Sustainable Forest Management include:

- Selective Logging: Harvesting trees in a way that preserves the overall structure, diversity, and regeneration potential of the forest.
- Reforestation and Afforestation: Planting trees to restore degraded areas or create new forests.
- Reducing Forest Degradation: Controlling such us uncontrolled logging, illegal land conversion and forest fires.
- Certification and Standards: Programs like the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC) promote SFM by setting standards for responsible forest management.

The sustainable use of forests, without damaging their ecological integrity, is one of the most environmentally friendly ways to safeguard human needs. In contrast, most other bioeconomy products usually require the prior clearing of forests or significant alterations to the original ecosystem for their production.

8.7 The Socio-economic Importance of Forests in a Bioeconomy—The Case of Germany

Germany is a highly industrialised country with a land area of nearly 360.000 km^2, of which 11.4 million hectares (32%) are classified as forest, 52% as agricultural land, and 13% as built-up areas, including transportation networks. Centuries of intensive use, degradation, reforestation, and afforestation have led to the current situation where most German forests are primarily production forests or 'cultural landscapes', with only a few areas being considered as near-natural (cf. Küster 1995, 2013; Leuschner and Ellenberg 2017). Despite this historical intensive use and exploitation, the forests have largely retained their original level of biodiversity, with the exception of large mammals, carnivores and predators. These species, which historically competed with humans, have been hunted to extinction. Among them are the bear, wolf, lynx, otter and large birds of prey such as eagles and vultures. Other species, such as the Auer Ochs (*Bos primigenius*) which still lived in central Europe at the beginning of the seventeenth century, are now extinct, while the wisent (*Bos bonasus*) came close to extinction at the beginning of the twentieth century.

Without human interference, Germany would be a forested country, characterised by broadleaf trees, mainly beech (cf. Leuschner and Ellenberg 2017). Beech-dominated forests would cover around 74% of the total forest area, followed by oak forests with 18%. However, through historical developments, German forests are now dominated by conifers, which cover 60% of the forest area, with

broadleaf forests only covering 40%. One main reason for this development is that conifers are easier to propagate and establish than broadleaf trees, especially on open lands. In the past, they were often the only viable option to re-establish forests, even though they were not evolutionary adapted to the sites they were planted on. Another economic reason was that charcoal, mainly made of hardwood, declined as an energy source. Consequently, softwood became much more valuable. Even in the production of salt, which consumed tremendous amounts of timber, softwood was preferable because it produced lower temperatures compared to hardwood, which could melt the salt pans. As a result, tree species composition changed in favour of softwood species. This trend was further exacerbated by the loss of the Second World War, which led to tremendous losses of tree cover due to 'reparation levies' (cf. Grundmann 2012). Softwood species were the most efficient and economically viable option to reforest these areas. Currently, the tree species proportions in Germany are as follows: 22% pine (*Pinus sylvestris*), 21% spruce (*Picea abies*), 17% beech (*Fagus sylvatica*) and 12% oak (*Quercus robur/petraea*). The remaining 28% are made up of 47 other tree species and species groups (BMEL 2024).

Nevertheless, there have been always voices claiming that the widespread coverage of tree monocultures is ecologically detrimental. These concerns were validated by several catastrophic storms that felled thousands of hectares of forest (not only softwood), resulting in millions of cubic meters of timber loss. Notably, in 1999, the hurricanes 'Lothar' (which caused 190 million cubic meters of damage across Europe) and 'Vivian' and 'Wiebke' (which led to 72 million cubic meters of damage in Germany alone) exemplified this.

In combination with climate change and increasing heat waves, these events also marked the beginning of the significant insect calamities currently observed, particularly in the artificial spruce forests of lowland Germany (Fig. 8.21). As a consequence of these developments, there has been a growing trend towards the return to the original or, at the very least, site-adapted species composi-



Fig. 8.21 Clear-cut area with felled and still standing dead spruce trees in the western Harz. (© Michael Welling)

Table 8.8 Forest ownership structure in Germany (Feil et al. 2018; BMEL 2024)

Forest ownership	Share of forest/%
Private[a]	48
Federal states	29
Corporations	20
Federal government[b]	3
Total	100

[a] About 50% of private forests are smaller than 20 hectares; [b]Especially military training grounds

tion and mixed stands, rather than relying on monocultures, especially in the light of the ongoing climate change.

Forests and their associated value chains hold considerable socio-economic importance. On average, each hectare of forest contains a timber stock of 335 m^3 and an annual timber increment of approximately 9.4 m^3, resulting in an annual timber production of more than 101.5 million m^3 (BMEL 2021).

With more than 1 million employees and a turnover exceeding 187 billion euros, the forestry and wood cluster is an economic heavyweight in case of Germany. The workforce is spread across more than 120,000 companies, with an average of fewer than nine employees per company. This highlights the unique structures and features of the cluster, which is dominated by small and micro-enterprises that often compete with companies from other sectors, some of which are more organised and professionalised. The challenge of further developing wood as a material and building material, as well as developing new marketable products for the future bioeconomy, presents significant obstacles for the forestry and wood cluster. Improved cooperation structures, particularly in small and medium-sized enterprises (SMEs), are essential in addressing these challenges (FNR 2024).

Forest distribution and ownership in Germany vary greatly across federal states. Rhineland-Palatinate and Hesse have the highest forest cover at 42% each, while Schleswig-Holstein has only 11%. The ownership structure is quite heterogeneous (Table 8.8) and is dominated by private owners. The private sector, that is private and corporate forests together, accounts for 68% of the total forest area and approximately 2 million owners (BMEL 2024).

8.8 The Future of the Forest-Based Bioeconomy: New Potentials and Climate Change Risks

Forests and forestry are central components of the bioeconomy. They are natural systems that provide a wide range of ecosystem goods and services, including raw materials, climate regulation, carbon storage, biodiversity conservation and various non-wood forest products (NWFPs). Together, these contribute significantly to the economy (Salzman et al. 2018).

With rising demand for renewable and sustainable products, along with increasing societal pressure to reduce greenhouse gas (GHG) emissions, parts of the forest industry are shifting towards producing innovative bio-based products to meet these needs (Hurmekoski et al., 2018; Lettner et al. 2018). At the product level, wood products are associated with lower GHG emissions throughout their entire life cycle compared to those made from non-renewable or emissions-intensive materials (Verkerk et al. 2022).

In the context of climate change, the forest-based sector can contribute to mitigation efforts through (i) carbon storage in forest biomass and soil, (ii) carbon storage in

wood products (e.g. ◘ Fig. 8.22) and (iii) material substitution. When wood is harvested and processed into products, the carbon remains stored within these products, depending on their use and lifespan.

The effects of substitution depend on several factors, including the type of wood product involved, the non-wood product it replaces, production technologies and efficiencies, and the end-of-life management of both wood and non-wood products. These factors can vary significantly, and the overall substitution effects also depend on the proportion of different forest products within the total product mix of a sector or country (Verkerk et al. 2022).

There is currently a limited understanding of substitution effects at market, national, or global levels, partly due to insufficient detailed data on wood end-uses and the complexities of identifying which materials are being replaced. While forest products can offer benefits over non-renewable, greenhouse gas (GHG)-intensive materials, increased production and consumption of these products carry potential risks. The extraction and production of raw materials for manufacturing have economic, social, and environmental impacts. Expanding the use of forest products could place additional pressure on forests and forest-dependent communities, and, if unsustainably managed, may result in forest degradation, biodiversity loss and reduced carbon stocks and storage (Verkerk et al. 2020).

The globally reported potentials for reforestation, afforestation and restoration vary widely (e.g. Bastian et al. 2019; Brancalion et al. 2019; FAO 2020a; ▶ The Global Restoration Information Hub). Moreover, the feasibility of large-scale Forest and Landscape Restoration (FLR) commitments remains uncertain at the landscape level in many regions (Fagan et al. 2020). However, it is evident that current efforts are insufficient, and greater ambition is needed to address ongoing patterns of deforestation and forest degradation. Strategies such as deforestation-free value chains and more efficient utilisation of bio-based materials through cascading use are essential to make meaningful progress.



◘ **Fig. 8.22** Metla House in Joensuu, eastern Finland, a wood buildhing made of wood of 24 native Finnish tree species. (© Iris Lewandowski)

This must address the demands of a growing population while incorporating sustainable and climate-smart forest management. The increasing uncertainty of climate change puts pressure on forest systems and their role as sources of bio-based resources. Policies and environmental management must consider these factors carefully, adopting a realistic rather than overly optimistic perspective on the future potentials of the forest-based bioeconomy. This includes a balanced understanding of the substitution effects of wood-based products in a world increasingly affected by climate change challenges such as wildfires, drought stress, pest infestations, and disease outbreaks.

The future of the forest-based bioeconomy holds significant potential for society but also presents challenges that require research and innovation to achieve sustainable and climate-smart forest management for future generations.

Questions

1. What are the specific features of forests?
2. Distinguish between the different forest types and their distinguishing features.
3. How do forests contribute to mankind's needs and to the bioeconomy?
4. What is the relevance of forests in addressing global challenges such as mitigating climate change?
5. What is sustainable forest management?

Answers

1. We can distinguish between two aspects: (A) the ecological characteristics of forests and (B) the classification for the purposes of monitoring.
   (A) Forests are ecologically characterised by their tree population—woody, upright, perennial plants and the resulting ecological characteristics. Compared to open land, they are characterised by a specific forest environment with a respective flora and fauna. We observe a specific forest climate with generally lower extremes compared to the open land, temperatures are more balanced, the relative humidity is higher, and air movement and light intensity lower. Forests also show specific soil properties with often high carbon accumulation in the topsoil. Depending on the type of forest, they have an extremely complex vertical structure with corresponding habitats for flora and fauna. For example, the canopy in tropical rainforests forms a highly diverse living environment in its own right.
   (B) Formal classification by e.g. FAO's FRA 2020 (greatly simplified):
   - Land spanning more than 0.5 hectares with trees taller than 5 m and a canopy cover exceeding 10%, or trees able to reach these thresholds in situ.
   - It does not include land that is predominantly used for agricultural or urban purposes, such as fruit tree plantations, oil palm plantations, olive orchards, and agroforestry systems where crops are grown under tree cover.
   - Forest can be divided into two major categories: 'naturally regenerating forest', which is predominantly composed of trees established through natural regeneration, and 'planted forest', which is predominantly composed of trees established through planting and or/deliberate seeding.
   - Bamboo, mangrove, and rubber wood stands are classified as specific forest categories.
2. We can distinguish the following different forest types:
   - *Boreal forests:* found in the northern hemisphere, mainly between 50–70° north, comprise the vast conifer-dominated forests of northern Europe, northern Russia, Canada and Alaska, also known as taiga. They are an impor-

tant source of pulp wood and construction timber.
- *Temperate forests:* mainly occur in the northern hemisphere between 35–55°, are characterised by more balanced climatic conditions than boreal forests. They are humid with precipitation ranging from 500 to 1000 mm/year, with a peak in rainfall during the summer. Broadleaf trees gain a considerable importance compared to the pine dominated boreal forest.
- *Mediterranean forests:* defined by specific climatic conditions rather than geography, these forests occur not only around the Mediterranean Sea but also in similar climates worldwide. The typical climate features, mild, rainy winters and very hot, dry summers, with sclerophylous vegetation and evergreen trees. Their economic importance concerning traditional forestry use is restricted, but they are home of, for example, the olive tree, cork oak or the pistachio. Additionally, one of the most important plantation trees, the Monterey Pine (*Pinus radiata*), stems from.
- *Tropical rainforests:* They are the world's most diverse forests, are characterised by average temperatures between 24 and 30 °C, and a minimum average annual temperature of 18 °C. Rainfall exceeds 1800 mm per year. The vegetation is dominated by a high diversity of woody plants, which can reach impressive heights of 30–50 m, sometimes even 70 m.
- *Mangroves:* They grow in the intertidal zone of tropical and subtropical coastlines, estuaries and deltas, adapted to regular inundation by saltwater requiring tolerance to salt as well as oxygen shortage, found throughout the tropics and subtropics. They are of considerable importance for coastal ecology and as spawning grounds for fish, respectively.

3. Forests serve mankind needs through:
   - Delivering wood and non-wood products
   - Delivering diverse ecosystem services
   - Providing recreational value
   - Storing carbon and helping climate change mitigation
4. In the context of climate change, the forest-based sector can contribute to climate change mitigation through: (i) carbon storage in forest biomass and soil, (ii) carbon storage in wood products and (iii) material substitution. When wood is harvested and products are made from it, carbon remains stored in these products depending on their end use and lifetime.
5. Sustainable Forest Management (SFM) is a comprehensive approach to managing and using forests in ways that maintain their biodiversity, productivity, regeneration capacity, vitality, and ability to fulfil ecological, economic and social functions. The goal of SFM is to ensure that the benefits provided by forests can meet the needs of present and future generations, while preserving the health and integrity of forest ecosystems.

Practices in Sustainable Forest Management include:
- Extraction of resources on a sustainable basis, as, for example, selective logging considering local environmental conditions and growth dynamics of the respective trees
- Reforestation and, where necessary, afforestation, with locally adapted species
- Avoiding forest degradation
- Monitoring and the application of certification and standards

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Blue Bioeconomy

Johannes Pucher



Fig. 9.0 Blue bioeconomy. © Ulrich Schmidt (► https://doi.org/10.1007/000-htm)

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This chapter describes the diversity of aquatic organisms from micro- and macroalgae, crustaceans, molluscs, and finfish from freshwater and marine systems which are used for food, feed, and other purposes. A large share of these aquatic resources is harvested from natural stocks by capture fishery. But nowadays, more than half of aquatic foods are produced in aquacultures of different intensities. These aquaculture systems differ depending on the requirements of the cultured organisms and on local circumstances. Aquaculture plays an important role in food and nutrition security and is an essential part of (circular) bioeconomy systems as it can be efficiently integrated into flows of nutrients, water, and feed resources.

Learning Objectives

After studying this chapter, you will…

- …be able to describe the origin of aquatic foods globally (see ► Sects. 9.1, 9.2 and ► 9.3).
- …be able to describe and discuss different capture fisheries and various aquaculture production technologies with its potentials and challenges (see ► Sects. 9.1 and 9.2).

9

Aquatic animals like fish, crustaceans, molluscs, and echinoderms, as well as micro- and macroalgae, are fundamental to a well-balanced, healthy diet due to their profile and content of essential amino acids, polyunsaturated fatty acids (e.g., eicosapentaenoic acid and docosahexaenoic acid), vitamins, and minerals (FAO 2024b). For the supply of aquatic food and feed, a large variety of aquatic species from numerous habitats of varying salinity (from freshwater to seawater) and different climate zones (polar zone to tropics) are used. Most of these aquatic organisms are poikilothermal, which makes the temperature of the surrounding water an essential factor for their biological activity and productivity.

On the one hand, aquatic food products are increasingly consumed as healthy and easily digestible food by richer consumers. On the other hand, aquatic animal-based protein resources are highly important for food and nutrition security in low- and middle-income regions and emerging economies. The annual per capita consumption of aquatic organisms has risen worldwide from 14.4 kg (1990s) to 20.7 kg (2022) and is expected to further rise (FAO 2024b). In 2022, aquatic animal-based foods accounted for 15% of the animal protein supply to humans and 6% of the total protein supply (FAO 2024b) making aquatic foods essential for the global protein supply.

In 2022, the global production of aquatic animal-based biomass reached 185.4 million tons, of which 164.6 million tons were used for human consumption and 20.8 million tons for other uses like fishmeal and fish oil production for feeds (FAO 2024b). The production of algae reached 37.8 million tons (FAO 2024b). The growth in world population, rising per capita consumption, and better access to global and local markets have led to an increasing global demand for aquatic food and feed resources (FAO 2024b). An increase of world production of aquatic animals to 205 million tons is expected by 2032 (FAO 2024b).

Of the 2022 total annual production of aquatic animals, 91.0 million tons were harvested by capture fisheries and 94.4 million tons were produced in aquaculture (Fig. 9.1). Since the 1990s, the growing demand for aquatic food cannot be satisfied by capture fisheries alone and has caused a steady increase in aquaculture production. Over the past two decades, total aquaculture production has grown at an average annual rate of 5.2%, making the aquaculture sector the fastest-growing food production sector (FAO 2024b), especially in Asia (Table 9.1). Since 2013, global aquaculture has reached higher production than capture fishery, with aquaculture having a share of 59% of global production in 2022 (FAO 2024b).

Aquacultural production is growing in developing and emerging economies in particular, leading to a strong global imbalance in geographical supply and demand in seafood, as 37.6% of seafood produced globally is exported (data 2022, FAO 2024b). In 2022, 70% of the global aquaculture production was conducted in Asia (FAO 2024b,

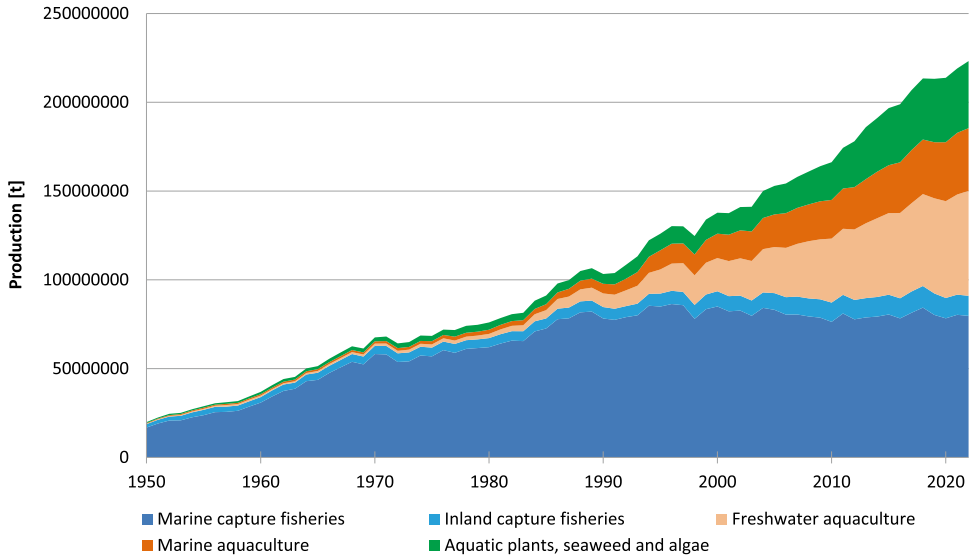


Fig. 9.1 Global production of aquatic foods from capture fishery and aquaculture over time (1950–2022) based on FAO (2024a)

Table 9.1 Aquaculture production by regions in 2022 (FAO 2024b)

	Production of aquatic animals [million tons]	Production of algae and seaweed [million tons]	Total [million tons]
Africa	2.316	0.188	2.505
Latin America and the Caribbean	4.313	0.021	4.335
Northern America	0.645	0.000	0.645
Asia	83.399	36.252	119.652
Europe	3.503	0.030	3.533
Oceania	0.235	0.012	0.248
Total	94.412	36.505	130.918

Table 9.1). Consequently, seafood products consumed in industrialized countries are often produced in developing or emerging economies. This makes harmonized and internationally accepted standards and regulations for the production, processing, and trading of aquatic foods essential to ensure an adequate level of protection for the consumer as well as improve welfare standards and environmental protection. The blue bioeconomy is projected to increasingly utilize aquatic resources for the more sustainable production of foods and other uses.

"*Blue bioeconomy*" incorporates any economic activity associated with the use of renewable aquatic biological resources to make products. Examples of these wide-ranging products include novel foods and food additives, animal feeds, nutraceuticals, pharmaceuticals, cosmetics, materials (e.g., clothes and construction materials) and energy. Businesses that grow the raw materials for these products, or that extract, refine, process, and trans-

form the biological compounds, as well as those developing the required technologies and equipment all participate in the blue bioeconomy" (EC 2023).

9.1 Aquaculture

"***Aquaculture*** is the farming of aquatic organisms, including fish, molluscs, crustaceans, and aquatic plants. Farming implies some sort of intervention in the rearing process to enhance production, such as regular stocking, feeding, protection from predators, etc. Farming also implies individual or corporate ownership of the stock being cultivated. For statistical purposes, aquatic organisms which are harvested by an individual or corporate body which has owned them throughout their rearing period contribute to aquaculture while aquatic organisms which are exploitable by the public as a common property resource, with or without appropriate licenses, are the harvest of fisheries" (FAO 1997).

Nowadays, more than 520 single species or groups of species (excluding plants, algae, and mammals) are cultured in marine, brackish, or freshwater aquaculture systems. Cultured aquatic organisms show a large variation in the nutritional requirements and feeding behavior (planktivorous, herbivorous, detrivorous, omnivorous, and/or piscivorous/carnivorous, see Excursus ► 9.1: "Feeding types of aquatic organisms"), including all trophic levels from primary producers (trophic level 1, phototrophic organisms), primary consumers (trophic level 2, consumers of trophic level 1 organisms), and secondary consumers (trophic level 3, consumers of trophic level 2 organisms) to top predators (trophic levels 4 to 5). A wide range of aquaculture production systems exist to accommodate the specific needs of the species and integrate aquaculture into the local/regional conditions.

Excursus 9.1. Feeding Types of Aquatic Organisms

Phototrophic organisms are able to transform light energy via photosynthesis into chemical energy by using carbon dioxide (CO_2) to synthesize organic compounds. Apart from the light energy, the phototrophic organisms take up nutrients and elements from the surrounding to synthesize complex compounds including carbohydrates, proteins, vitamins, secondary compounds, and lipids including poly-unsaturated fatty acids. These processes are the base of the food chain, and all the following trophic levels are depending on this biomass. Aquatic examples are single-cell microalgae like *Nannochloropsis* spec., and structurally more complex seaweeds like *Laminaria* spec.

Planktivorous organisms and life stages are feeding on plankton, which are small aquatic organisms living in the water column. Plankton is differentiated into phytoplankton, which are phototrophic single or multi-cell algae, and zooplankton, which are small species or larvae of crustaceans, molluscs, fish, and insects. Planktivorous organisms might selectively feed on certain sizes and species of plankton or feed non-specifically on all sizes of plankton. Typical examples of planktivorous fish species are the silver carp (*Hypophthalmichthys molitrix*) filter-feeding on small-sized phytoplankton and zooplankton, while the bighead carp (*Hypophthalmichthys nobilis*) filters larger sized plankton (especially zooplankton). Typical filter-feeding bivalves are the true oyster (*Magallana gigas*) and the blue mussel (*Mytilus edulis*).

Herbivorous organisms and life stages can digest aquatic and/or terrestrial plant material by a combination of anatomic adjustments (e.g., long intestine), excretion of digestive

enzymes and specific intestinal microbiomes. A typical example is the grass carp (*Ctenopharyngodon idella*).

Omnivorous organisms feed diverse types of feeds including plant material, detritus, and aquatic animals like insects, worms, bivalves, crustaceans, and small fish. An example is the common carp (*Cyprinus carpio*).

Detrivorous organisms and life stages are feeding on decomposing organic substances (detritus) from plants or animals including feces and the decomposing microbiomes. Aquatic examples are the lugworm (*Arenicola marina*) while most filter-feeding organisms (like mussels and oysters) partially also digest suspended detritus particles.

Carnivorous/piscivorous organisms and life stages are predators on other animals like insects, fish, crustaceans, molluscs, and mammals. Typically, piscivorous species are supplying their energy requirements mainly from protein and lipids, due to their limited ability to digest carbohydrates. The digestive tract typically includes a stomach with a more acid milieu to digest proteins with specific digestive enzymes. Piscivorous fish are of high or very high trophic level and depend on large biomasses along the food web. There are many examples like the Atlantic salmon (*Salmo salar*), saithe (*Pollachius virens*), and bonito (*Sarda sarda*) and many more.

Aquaculture production systems differ greatly with regard to their intensity of production, which can be classified (Fig. 9.2) according to the yield, stocking density, level of external feed/fertilizer inputs, dependency on natural food resources, management/technical requirements, capital, labor, and risks (Edwards et al. 1988; Tacon 1988; Prein 2002). In general, aquaculture production systems are classified into three intensities (extensive, semi-intensive and intensive aquaculture) and are integrated differently into the spatial bioeconomies and biomass flows.

In *extensive aquaculture*, aquatic organisms from mainly lower trophic levels are grown solely on natural feed resources (e.g., bacteria, phytoplankton, zooplankton, zoobenthos, detritus, and prey fish) without substantial inputs of external feed or fertilizer. The systems are most often run as *polycultures* (combination of several species with different feeding niches in the same pond) for local and regional markets. The stocking densities per area and the annual yields are low due to the limited productivity of the natural feed resources. Extensive aquacultures require only low levels of technical equipment, management schemes, and financial investment, but large areas of water per yield, as the internal production of feed resources is entirely based on natural primary (algae) production within the ponds. Extensive aquaculture systems are only applicable in areas where suitable surface waters are abundant and are not polluted. These natural aquaculture systems are often highly important for the preservation of biological biodiversity as they provide suitable habitats for a wide range of flora and fauna. As no external feed and fertilizers are used, extensive aquaculture systems act as a nutrient sink and counteract eutrophication. In low- and middle-income countries in particular, extensive aquaculture plays an important role for the food security of poorer communities, as minimal management and inputs are required to produce highly nutritious food resources. The future expansion of extensive freshwater aquaculture systems is very limited due to the limited availability of suitable water resources. Required are the more efficient use (intensification) and recycling/multiple use of freshwater in integrated systems without increasing the risk of contamination with undesired substances that reduce the safety of food products.

A special form of extensive aquaculture is *extractive aquaculture* in which filter-feeding aquatic species are cultured in more eutrophic waters. The most predominant example is the production of bivalves (e.g., mussels, oysters) which are grown in coastal waters and feed on plankton and detritus. Similarly, seaweeds are grown in coastal waters and take up dissolved nutrients. These extractive aquacultures have high potential as they counteract eutrophication, especially in coastal zones, but care

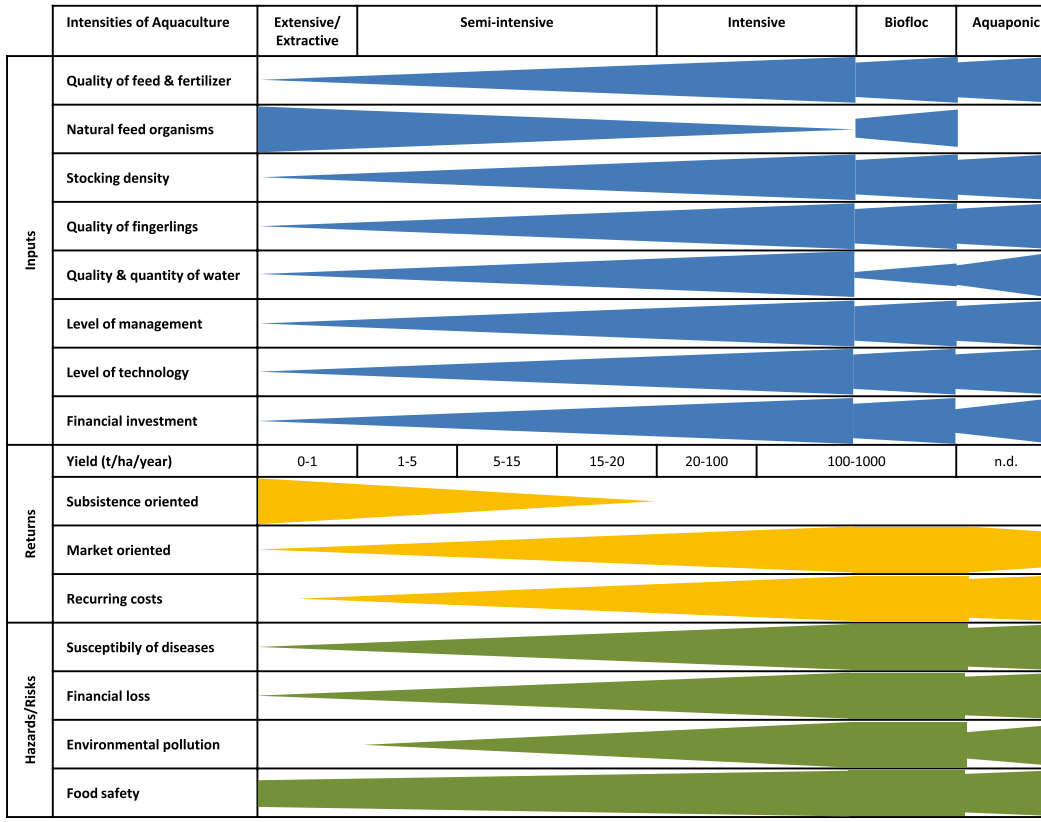


Fig. 9.2 Classification of different aquaculture production systems according to their intensities of input, returns and hazards/risks. (Redrawn and expanded from Edwards et al. (1988) in cooperation with U. Focken)

should be taken regarding potential contamination with marine toxins, pathogens and undesired substances that are harmful for human health.

In *semi-intensive aquaculture*, aquatic organisms are grown in natural or constructed ponds (Fig. 9.3) on a combination of external supplemental feed and natural feed resources supported by organic or inorganic fertilizer inputs in combination with a suitable water management. These systems are most often run as polycultures of several species of lower trophic levels for regional or national markets. To effectively utilize the protein-rich natural feed resources, external feeds often contain high levels of carbohydrates/energy to supply the cultured species with the required nutrients in a balanced and effective way (De Silva 1995; Viola 1989). In low- and middle-income countries, by-products of lower quality (e.g., press cakes, brans, and manure) are often used as feed and fertilizer resources. Semi-intensive aquaculture is characterized by medium stocking densities, moderate use of technical equipment (e.g., aeration) and medium management requirements. As with extensive aquaculture, semi-intensive aquaculture offers a range of habitats for flora and fauna and stabilizes biodiversity. On a global scale, semi-intensive aquaculture is extremely important for the supply of highly nutritional food and is most often highly integrated into spatial bioeconomies and biomass flows (e.g., water, feed, and fertilizers). In low- and middle-income countries of Asia and Africa, semi-intensive aquaculture in integrated agriculture aquaculture (IAA) systems is very important. These systems integrate agricultural production with livestock husbandry and pond aquaculture. By-products from each farming activity are used as feed or fertilizer for another farming



Fig. 9.3 Semi-intensive carp polyculture in a pond in Vietnam. (© Johannes Pucher)

activity, leading to a circular bioeconomy at farm or regional level. However, in such IAAs, an intensification of one farming activity (e.g., application of pesticides or inorganic fertilizers) has a direct impact on the efficiency of the entire system and may also affect the safety of their products (Pucher et al. 2014, Schlechtriem et al. 2016). A sustainable and safe expansion of this type of aquaculture needs to be well integrated into the regional situation. But the largest part of an increased future production necessary to supply the rising demand can only be achieved by sustainable intensification of aquaculture (Tacon et al. 2010; FAO 2024b).

Intensive aquaculture is the production of aquatic species, mostly omnivorous or piscivorous/carnivorous species, in monocultures for large national/international markets. It enables the highest control over the culture conditions including water quality, feed utilization, hygienic conditions, and animal health management. In intensive aquaculture, the cultured species are grown solely on external feeds, which are specifically formulated and produced to supply them with all required nutrients and energy, thus enabling an efficient and maximized utilization of resources such as water and feeds. These systems are specifically designed to adjust and stabilize the culture conditions to the needs and requirements of the cultured species (e.g., oxygen supply, temperature, currents, salinity, and pH). The use of technical equipment (aerators, water quality monitoring, filters, nitrification and denitrification units, pumps, disinfection units, temperature controls, automatic feeders etc.) enable high stocking densities which is highlighting the needs for welfare standards. This high-intensity aquaculture allows the highest yields, space efficiency, monetary return and standardization of products, but necessitates a high level of monetary investment, management and skilled staff (Fig. 9.4). Potential risks are insufficient quality and safety of feeds and water resources, environmental pollution and eutrophication by effluents, genetic mixing of aquaculture escapees and wild stocks, animal welfare issues, inadequate utilization of veterinary medicines (e.g., antibiotics) and production technologies, as well as outbreaks of diseases, technical failure and price competition on national/international trading.

Intensive aquaculture is conducted either in net cages (Fig. 9.4) or in land-based flow-through systems, pond systems (Fig. 9.6) or closed recirculation aquaculture systems (RAS, Fig. 9.5). Net cages are



Fig. 9.4 Intensive net cage culture of salmon in Norway. (© Johannes Pucher)

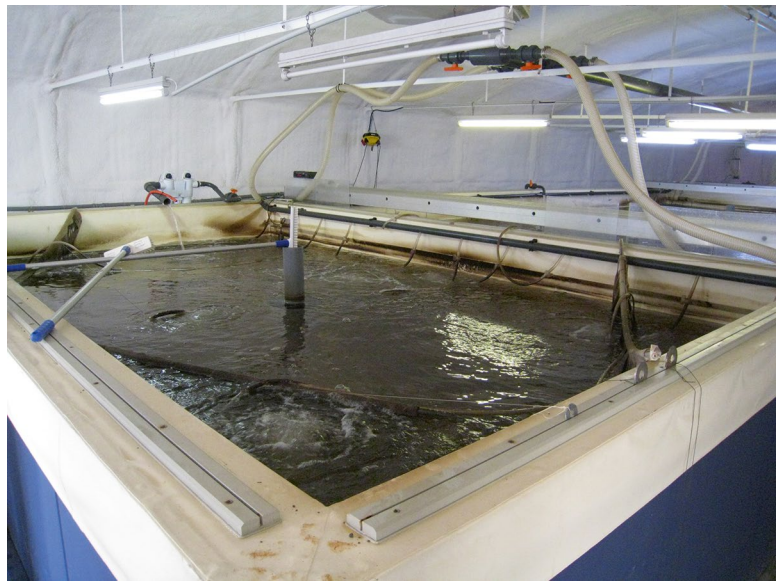


Fig. 9.5 Intensive indoor shrimp production in a recirculating aquaculture system in Germany. (© Johannes Pucher)



Fig. 9.6 Intensive outdoor shrimp production in a pond system in Vietnam. (© Johannes Pucher)

installed in rivers, lakes or marine waters and enable direct contact of the cultured species with the surrounding environment via the water, which supplies the animals with oxygen and flushes out faeces and dissolved metabolites. This type of aquaculture is affected by the surrounding environment through potential diseases and parasites, which may attack the cultured species, but also directly affects the environment through the effluent water and emitted nutrient, escapees as well as diseases and parasites, which highlights environmental concerns and makes the management and the site selection of such production highly important while more offshore production systems are increasingly investigated.

Closed recirculation aquaculture systems (RAS, Fig. 9.5), pond systems (Fig. 9.6) and flow-through systems are constructed indoor or as outdoor tanks and ponds. In these so-called land-based systems, the water flow can be better controlled, allowing higher protection of cultured species from external influences (e.g., parasites, contaminated waters) and also higher protection of the environment, as effluents can be filtered and treated before release. Flow-through systems direct water through the culture raceways, supplying oxygen to the organisms and flushing out metabolites and feces. By contrast, RAS recycle the water by filtering solid wastes out and oxidizing the highly toxic ammonium (main metabolite of the culture species' protein metabolism) to less toxic nitrate. This nitrification allows multiple recirculation of the water and thus a higher water use efficiency. Inclusion of denitrification units can even increase this multiple water use, allowing highly controlled production with minimal use of water resources.

Intensive aquaculture offers high potential for future production due to its high productivity, efficiency, and controllability. But an increase in intensive aquaculture production is creating concerns about animal welfare, environmental sustainability, higher demand for classical feed resources (e.g., fishmeal and fish oil) and land/water to produce plant-

based feed resources (Tacon and Metian 2008). The limited availability and increasing price of fishmeal and fish oil for the intensive production of piscivorous species and increasing consumer awareness is pushing the sector to minimize the use of fishmeal/fish oil and replace them with alternative, plant-based resources. Nowadays, the fishmeal content in aquafeeds is reduced to a minimum (Ytrestøyl et al. 2015) to supply essential amino acids which are not available in sufficient amounts in alternative plant-based feed resources, yet. Soybean protein in particular is often used in aquafeeds. However, globally other plant-based as well as animal-based by-products from other branches of the bioeconomy are also used (Hardy 2010; Hernández et al. 2010), including press cakes and protein extracts from plant oil production, protein extracts from single-cell technology, blood and bone meal, insect meal, and unsaturated fatty acids from vegetable and algae oils.

Other novel methods of integrated aquaculture systems are increasingly being developed and applied, which follow a more direct implementation of a circular bioeconomy and focus on a more efficient use of nutrients and water.

Integrated multi-trophic aquaculture (IMTA) are combinations of several aquatic species of different trophic levels which are co-produced in order to utilize the applied nutrients more effectively and reduce environmental impacts. A prominent example is the combination of intensively fed carnivorous fish with detrivorous, filter-feeding and/or phototrophic species such as crustaceans, mussels, and/or seaweed. This might be realized in cascades in open waters or in more enclosed, land-based systems where the effluents from the fish are directed over crustaceans, mussels and/or seaweed cultures. The filtering species filter out solid particles and the macroalgae feed on dissolved nutrients. This concept allows the partial binding of emitted nutrients from intensive aquaculture to supply additional products (e.g., mussels, seaweed). Depending on the local circumstances and regulatory frameworks, different types of IMTA are developed, while globally, there are many types of different IMTA systems being already implemented, especially in Asia (EC 2020).

Another form of modern integrated aquaculture is the combination of intensive aquaculture (of fish) and hydroponic production of plants like herbs and vegetables. These so-called *aquaponic systems* are designed to utilize the excreted dissolved nutrients from aquaculture production as fertilizer for plants. Some systems even recycle water from evapotranspiration. This increases both nutrient and water use efficiency. These systems are currently being promoted for (peri-)urban regions to supply urban niche markets with locally produced food products. Additionally, waste heat from industrial activities can be utilized to increase their competitiveness. However, the competitiveness and efficiency of aquaponic production systems is presently debated.

Biofloc systems are increasingly applied globally and are a mixed form of semi-intensive and intensive aquaculture. Here, fish or shrimp are kept in intensively managed aquaculture tanks or ponds with minimized water exchange. In addition to the feed for the cultured species, low-value, carbohydrate-rich by-products (e.g., molasses and vinasses) are applied as an energy source for a microbial community of heterotrophic and chemotrophic bacteria. These bacteria organically bind the nutrients excreted by the culture species (e.g., nitrogen and phosphorus) to form so-called bioflocs, which are eaten by the culture species. High water aeration is necessary to supply the culture species and bacterial community with sufficient oxygen and keep the bioflocs suspended in the water so that dissolved nutrients are efficiently captured and serve as an internally recycled feed resource. Such systems promise a higher nutrient efficiency and productivity of used water sources, but potential risks include the accumulation of undesirable substances in the system and hygienic conditions.

As described above, aquaculture can take a number of different forms and operate at various scales, while it can vary from subsistence-oriented small-scale fish farming in the family pond to the industrial-scale production for international markets. Aqua-

culture is part of complex value chains and is influenced by a range of environmental, societal, and governmental factors. For future aquaculture production of healthy and safe food products, it is important to focus on environmental, social, and economic sustainability and integrate aquaculture into the regional surrounding circumstances. These surrounding circumstances include the availability and quality of water resources, feed resources, know-how of workers and public, availability of technology, acceptance within the society for the production systems and products, permitting regulatory framework on environmental performance, production licenses, water use, animal welfare, market demand and prizes, production costs, seasonality, risks of food safety and biosecurity, availability and quality of stocking material, climate change, and post-harvesting/processing. Risk assessments, value chain analysis, and market surveys might be needed to mitigate potential risks. In general, it is more resource efficient to culture species of lower trophic level and increase the utilization of by-products by establishing production chains with alternative feed resources. The choice of production method is highly depending on local conditions and therefore, it might be suitable to establish polycultures/multi-trophic systems in one location but more suitable to establish intensive recirculating aquaculture systems (◘ Fig. 9.5) in another location. Improving animal welfare and sustainability of aquaculture as well as implementing eco/welfare-labelling and quality assurance/certification are targeted to increase the consumer acceptance.

9.2 Fisheries

For human food production, capture fisheries mainly supply the markets with organisms of higher trophic levels, like piscivorous or carnivorous fish, molluscs species and crustaceans (Neori and Nobre 2012; Tacon et al. 2010). Species of lower trophic level (especially pelagic fish species) are used for food but also for non-food purposes including the production of fishmeal and fish oil, which are dominantly used as feed sources in aquaculture (Shepherd and Jackson 2013; FAO 2024b). While in 2000 about 25.0 million tons (18.6% of global production) of the aquatic biomass was used for non-food purposes, in 2022 the non-food use fraction was reduced to 20.8 million tons (11.2 % of total production, FAO 2024b). In 2021, more than 80% of fishmeal and more than 70% of fish oil were used as feed resource for aquaculture feeds (FAO 2024b based on IFFO estimates) as fishmeal can be used more efficiently for feeds in aquaculture production than for feeds in livestock systems (Naylor et al. 2009). Nowadays, about 34% of global fishmeal and 53% of global fish oil is obtained from fish by-products of the fish processing industry leading to an internal loop of this high quality and high-prized resource within the industry of aquatic foods (FAO 2024b based on IFFO estimates). In total volume, small pelagic fish species (see Excursus ▶ 9.2) like Anchoveta (*Engraulis ringens*), Atlantic herring (*Clupea harengus*), European pilchard (*Sardina pilchardus*) and Pacific sardine (*Sardinops sagax*) are having a large share in the total annual capture fishery production (FAO 2024b). Capture landings for food and non-food purposes are dominantly harvested in seas and oceans (79.7 million tons in 2022), whereas 11.3 million tons were landed from freshwater systems (FAO 2024b).

Over the past decade, the amount of aquatic animal biomass landed globally by capture fisheries has been maintained at a relatively constant level through the utilization of ever more effective fishing gear and landing technologies, and by the overexploitation of several natural stocks (Pauly 2009; FAO 2024b). The utilization and management of stocks of fish species differ regionally. While the majority of fish stocks are maximally sustainably fished, an increasing share of stocks are overfished and a declining share of stocks are underfished (FAO 2024b), which is showing the increasing pressure on natural stocks and highlights the importance on sustainable fish stock management.

Excursus 9.2 Small Pelagic Fish Species

Small pelagic fish species (< 25 cm total length) are typically planktivorous fish species which are available in large biomasses (Bavinck et al. 2023). Its selective capture fishery was shown to be the animal-sourced food biomass with the lowest green-house gas emission, the lowest energy use, and very low emissions of eutrophication and acidification potential (Hilborn et al. 2018). Stocks of small pelagic fish vary in abundance over time and by species and region. But across stocks, there has been a remarkable stability in biomass over the last decades (Hilborn et al. 2022).

Small pelagic fish species are predominantly used for feed resource production. In the recent years, the importance of small fish species as food (in contrast to its use as feed) was highlighted. Small fish species for food are often processed as whole fish including the bones, head, skin and viscera resulting in a source not only of animal-based protein and fatty acids but also of several essential micronutrients like minerals (especially calcium, zinc, iodine, iron) and vitamins (especially vitamin B12, vitamin D) and are playing an important role for food security in many countries (Bavinck et al. 2023; Kjellevold et al. 2023; Nölle et al. 2020; Wessels et al. 2023). But apart from the nutritional benefits, also potential food safety issues (like microbial hazards and contaminants) need to be monitored and managed to assure the health of consumers and nutritional benefit (Hasselberg et al. 2020; Wessels et al. 2023).

9.3 Macroalgae and Microalgae

Macro- and microalgae are a large and highly diverse group of phototroph organisms in freshwater, brackish, and marine systems in all climate zones. The productivity of micro- and macroalgae is mainly depending on conditions like the light intensity and wave-length composition, the content of different dissolved nutrients in the water, the availability of carbon dioxide, salinity, water temperature and water pH (a measure of acidity or alkalinity). About 50 species or groups of species of aquatic plants, seaweeds and algae are produced in aquaculture, while about 70 species or groups of species of aquatic plants, seaweeds and algae are harvested from the wild (FAO 2024b) including green seaweeds (e.g., *Ulva*) and brown seaweeds (e.g., *Sargassum* and kelps) (EC 2023). With the ability to transform light energy via photosynthesis into organic compounds, algae are the base for the entire aquatic food web, form the largest aquatic biomass, and feed all the trophic levels above. Apart from the organic energy source, algae form the feed base also for other compounds like protein and several vitamins, but also specific compounds like poly-unsaturated fatty acids (especially omega-3 fatty acids).

Biomasses from micro- and macroalgae are increasingly used as resource for food, feed, cosmetic, medicine, and energy, but are also discussed as materials for many other uses (e.g., construction materials, cloths, bio-based chemicals, fertilizer). Algae and seaweeds are used for human nutrition, especially in Asia, but have recently also been increasingly used in Western cuisine. Strong drivers for the development of bio-economies based on micro- and macroalgae are the capture of carbon, reducing land uses for the production of biomasses, reducing the dependence on animal-proteins and finding alternatives to petrochemicals (EC 2023).

Macroalgae and seaweeds are either harvested from naturally grown marine stocks or are specifically cultured in extractive aquaculture systems in which sessile macroalgae are attached to structures like ropes or frames which are installed at suitable sites at the coastline. Given the challenges of multiple and conflicting interests in using coastal zones (e.g., transportation, tourisms, wind energy parks), aquaculture of seaweeds is envisaged to be implemented more offshore while challenges like the harsh offshore conditions and transportation costs need to be overcome.

As aquatic macroalgae are assimilating dissolved nutrients from the water, their production can be coupled with other nutrient-emitting intensive aquaculture production systems, which together create multitrophic aquaculture systems (IMTA, see above). In the selection of suitable production sites for macroalgae, specific focus must be put on the occurrence of environmental contaminants, which otherwise might be assimilated in macrophytes leading to food safety concerns for the consumer.

The aquaculture of macroalgae can be managed in a way that the cultivation site produces food for humans but in addition generates habitats for a wide range of natural species to increase the natural species diversity in the cultivation area. Consequently, the aquaculture of macroalgae can be managed by combining food production, assimilation of dissolved nutrients and habitat creation and resilience in aquatic environments (Vogliano et al. 2024).

In contrast to macroalgae, microalgae are cultivated in intensive production units on land. The various algae species differ in their culture conditions, nutrient, and light requirements and in their nutritional components. The type of nutrient solution and the environmental conditions in the production cycle allow, to a certain level, the control of the compound composition of the cultured algae. On a larger scale, microalgae are cultured in open-pond systems. Although microalgae can be produced in open pond or raceway systems with sunlight, the risk of contamination with unintended algae species and algae consumers is very high, which might affect both productivity and product quality and safety. Further, these open systems are highly influenced by environmental factors from the surroundings, which include fluctuations of light conditions and temperature or the contamination with potentially pathogenic bacteria and viruses. This is limiting the predictable production of safe and high-quality products. Current developments in the production and use of microalgae are summarized in ▶ Chap. 10.

In Europe, major challenges in the production and use of micro- and macroalgae are factors like high production costs, low scale production, limited knowledge of the markets and consumers, limited knowledge of risks and environmental impact of algae cultivation and fragmented governance frameworks (EC 2023).

Questions

1. What organisms are covered under the term aquatic food?
2. What is the difference between capture fishery and aquaculture?
3. What differentiates extensive, semi-intensive, and intensive aquaculture systems and what advantage and disadvantages do these different systems have?
4. What is the benefit of more integrated aquaculture systems and what challenges do they have?
5. What are the different feeding types of aquatic organisms and how does this affect the respective aquaculture system?

Answers

1. For the supply of aquatic food, humans use a wide range of different aquatic organisms ranging from vertebrates, arthropods, molluscs, and echinoderms, as well as micro- and macroalgae.
2. Aquaculture is the farming of aquatic organisms including fish, molluscs, crustaceans, and aquatic plants while capture fishery is harvesting organisms from natural resources.
3. In intensive aquaculture systems, the cultured organisms receive the feed from external feed resources while in extensive systems, the cultured organisms are not actively fed but directly feed on natural feed resources (phytoplankton, zooplankton, and zoobenthos). Semi-intensive systems are systems that combine external feed resources and natural feed resources. These diverse systems enable an efficient integration into local resource conditions.
4. Integrated aquaculture systems enable the efficient cycling of nutrients

between aquaculture and agricultural systems using underutilized resource steams. The sustainable production of safe foods and feeds in integrated systems necessitates a holistic approach and a suitable regulatory framework.

5. Aquatic organisms are showing various feeding types ranging from planktivorous, herbivorous, omnivorous, detrivorous to carnivorous/piscivorous organisms. The feeding type and species-specific requirements in nutrition and husbandry are essential to design suitable aquaculture systems to meet the requirements of the aquatic organisms.

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Microalgae

Sebastian Weickert and Konstantin Frick

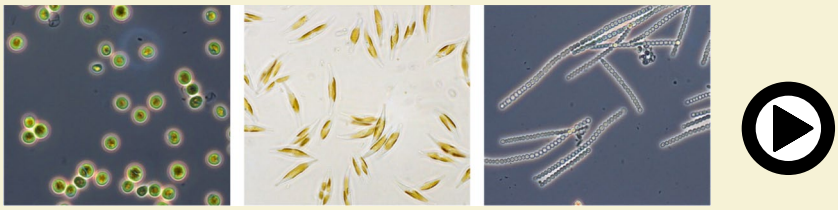


Fig. 10.0 Microalgae. (©Fraunhofer IGB) (▶ https://doi.org/10.1007/000-htn)

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Microalgae belong to the oldest forms of life, are found all over our planet and can be used commercially to produce specific food, feed and bio-chemical compounds. There are many microalgae strains that differ fundamentally in cell size, cell wall formation and biomass composition. In this chapter, the methods of microalgae cultivation and processing of microalgae-based biomass are described and compared. The cultivation process is performed in various open or closed bioreactor systems in salt, brackish or freshwater medium under different limited controlled conditions. Special processing requirements apply to the extraction of valuable compounds from microalgae biomass and further use of the residual biomass, especially in cascade utilization. By applying successive extraction procedures, both the principal fractions like proteins and lipids as well as high-value components such as pigments can be obtained sequentially from the microalgae biomass. In general, the chemical characteristics and market specifications, for example, the required degree of product purity, determine the downstream processing technique. In the last of the three sub-sections, a link is made to the biorefinery concept. The integration of microalgae cultivation into a biorefinery concept requires the closing of nutrient cycles, the utilization of residual flows such as nutrient-rich wastewater and industrial waste heat, and the ensuring of mild extraction processes that both maintain the functionality of the biochemical compounds and enable the extraction of further cell components.

Learning Objectives

After reading this chapter, you will…

- …be able to summarize the definition, metabolism and capability of microalgae. (see ► Sect. 10.1).
- …be able to describe the advantages and disadvantages for the cultivation of microalgae in different open or closed bioreactor systems. (see ► Sect. 10.2).
- …be able to discuss the possibilities and limits of downstream processing of microalgae biomass. (see ► Sect. 10.2.3).
- …be able to discuss the possibilities and challenges of integrating microalgae cultivation into the biorefinery concept. (see ► Sect. 10.2.3).

10.1 Natural Renewable Resource Microalgae

Microalgae belong to the oldest forms of life and are found all over our planet. They are mainly spread in water (salt, brackish, and fresh), but are also found on the surface of all kinds of soils in a wide range of environmental conditions. They have a high tolerance for different ranges of pH values, temperature, turbidity, salinity, and concentrations of oxygen and carbon dioxide (Barsanti and Gualtieri 2006). They are one of the most important global biomass producers, at the beginning of every aquatic food web and provide a large contribution to global oxygen production.

Microalgae are unicellular or simple multicellular structured organisms with chlorophyll a as photosynthetic (see Sect. ► 5.2 on photosynthesis) active pigment and a thallus, that is, a plant-like body that is not divided into roots, stems and leaves. Eukaryotic (comprising the genetic material in the form of chromosomes within a distinct nucleus) and prokaryotic (genetic material neither within a distinct nucleus with a membrane nor other specialized organelles) autotrophic organism are united in this definition (Tomaselli 2004). An autotrophic organism is defined as an organism that can convert abiotic sources of energy into energy stored in organic compounds. A photoautotrophic organism captures light and uses its energy to convert carbon dioxide (CO_2) via photosynthesis into chemical energy in the form of carbon-rich biomass. The main classes of eukaryotic autotrophic microalgae are classified after their light-harvesting photosynthetic pigments. There are *Chlorophyta* (green algae), *Rhodophyta* (red algae), *Chrysophyceae* (golden algae), and *Phaeophyceae* (brown algae). The class of *Cyanophyceae* or blue-

green algae is oxygenic eubacteria which can be divided into *Prochlorococcus* and *Synechococcus*. Also, cyanobacteria differ on account of their photosynthetic pigments phycobilisomes (*Synechococcus*), and divinyl chlorophyll a and b (*Prochlorococcus*). There are three classes of photosynthetic pigments: chlorophylls (green colour), carotenoids (yellow orange color) and phycobilins (red, blue, or orange color) (Masojídek et al. 2013; Sexton und Lomas 2018).

Microalgae can produce a large number of substances that are of interest to various sectors, including the food, feed, cosmetics, and pharmaceutical industries. The chemical composition of the approximately 135,000 known species worldwide varies widely (Granata 2017). The strain and mainly environmental parameter, such as temperature, illumination (light or dark), pH value, the mineral content of the ambient medium, CO_2 supply, mixing velocity, population density, growth rate, and microalgae physiology, strongly impact their chemical composition. They can produce large quantities of fatty acids in the form of triacyl-glycerides, proteins, or polar membrane lipids with omega-3 fatty acids (polyunsaturated fatty acids like eicosapentaenoic and docosahexaenoic acid), as well as a broad variety of carotenoids, phytosterols, vitamins, and minerals. The aim of scientists and industry is to use these compounds in food production without changing their techno-functional, nutritional, and physiological properties. Microalgae tend to produce large amounts of proteins when there is sufficient nitrogen and phosphorous supply. These proteins can constitute up to 60% of the total dry cell mass and appear very suitable for food and feed purposes, since the amino acid profile is in balance with WHO/FAO recommendations (Becker 2007). When microalgae cells are cultivated under conditions of nitrogen or phosphor starvation, some species (e.g., *Chlorella vulgaris*) can accumulate huge amounts of triacyl-glycerides consisting of glycerol and saturated and mono-unsaturated lipids. In addition to the main products, microalgae biomass can include several high-value by-products such as carotenoids (e.g., astaxanthin, β-carotene, fucoxanthin, and lutein) and phytosterols, which are of interest considering their antioxidant and anti-inflammatory properties (Ahmed et al. 2014; Ahmed et al. 2015; Macías-Sánchez et al. 2007; Francavilla et al. 2010).

> ***Microalgae*** are unicellular or simple multi-cellular structured organism with chlorophyll a as photosynthetic active pigment and a thallus not differentiated into roots, stem, and leaves. Eukaryotic and prokaryotic autotrophic organisms are united in this definition.

10.2 Microalgae Cultivation and Processing

10.2.1 Microalgae Cultivation—Upstream Processing

There are two main categories of cultivation systems: open ponds and closed photobioreactors (PBR). The possible growth conditions of microalgae for industrial production show a wide range: from phototrophic or mixotrophic in transparent glass or plastic cultivation systems with artificial (indoor) or natural sunlight (outdoor) to heterotrophic in opaque steel fermenters, from salt (seawater), brackish to fresh water. Other factors like pH value, temperature, nutrients, and aeration are important for optimal growth. Furthermore, the different systems vary in their light utilization efficiency, their ability to control temperature, the hydrodynamic stress placed on the microalgae, and their scalability from laboratory to industrial scale.

There are two types of *open cultivation systems*: natural water (lakes, lagoons, ponds) and artificial ponds or containers (Fig. 10.1). Artificial big ponds, tanks, circular ponds, and raceway ponds are simply scalable, flexible constructions made of low-cost materials and are easy to operate with low energy demand. Disadvantages are the strong dependence on the regional climate



Fig. 10.1 Open pond cultivation system in a large greenhouse with a volume of 30.000 litre to produce microalgae biomass from *Arthrospira platensis* in Ahlen, North Rhine-Westphalia, Germany. (© Deutsche Algengenossenschaft e.G.)

conditions, poor light utilization, and mass transfer rates resulting in low biomass productivities and final densities, which cause high harvesting costs. Other challenges are high water demand through evaporative losses, no options for temperature control, diffusion of CO_2 to the atmosphere, requirement of large areas of land, and high risk of culture. Only few microalgae strains are suitable for production in open ponds. Raceway ponds are the most used designs worldwide (95% of global microalgae production). They consist of a circuit of parallel channels (180° curves) of plastic or rubber sheet, in which the microalgae suspension is circulated at a low depth from 10 to 15 cm by paddle wheels. For a better mass transfer, they are equipped with sumps or mixing columns to increase the contact between gas and liquid (transfer efficiency up to 70%). The most widely cultivated microalgae on a commercial scale are *Arthrospira platensis*, *Chlorella vulgaris*, and *Dunaliella salina* for more than 30 years. They can tolerate extreme growth media like alkaline and highly saline ones, which are unsuitable conditions for competing species (Acién Fernández et al. 2013; Ugwu et al. 2008).

Photobioreactors (PBRs) are closed cultivation systems for phototrophic organisms made of glass or flexible or rigid plastic to strictly limit the direct exchange of gases, liquids (e.g., rain), and particles (microbes, insects, dust) between the culture in PBRs and the atmosphere. The material used influences the scalability and manageability of microalgae cultivation plants. Plastic PBRs are less expensive, lighter, and thus easier to replace than glass; in contrast, glass is highly transparent, more resistant to weathering and chemicals, thus easier to clean and more durable. A variety of designs have been developed to achieve high efficiency of light conversion and mass transfer, while avoiding damage to cells caused by pH and temperature gradients, oxygen accumulation and biofouling. In practice, two types of PBRs are primarily used: tubular (see Fig. 10.2) and flat plate PBRs. A comparative analysis of the reactor systems is presented in Table 10.1. The designs differentiate in relation to light gradients and light/dark cycles, surface to volume (S/V) ratio, mixing and degassing devices. There are also operational differences: air or pump-mixed and single-phase (separate gas



Fig. 10.2 Tubular photobioreactor in a greenhouse setting illuminated by sunlight in Nuthetal, Brandenburg, Germany (©IGV Institut für Getreideverarbeitung GmbH under license CC BY-SA 3.0 ► https://creativecommons.org/licenses/by-sa/3.0/)

Table 10.1 Advantages and limitation of open and closed microalgae cultivation systems (Brennan and Owende 2010; Bumbak et al. 2011; Ugwu et al. 2008)

Production system	Advantages	Limitations
Open cultivation systems		
Open pond	Relatively low-cost option Easy handling (e.g., cleaning) no-agriculture land required Low energy demand Easy and low maintenance requirements	Poor mass transfer, photosynthetic efficiency and biomass productivity Require large amount of land Little control of cultivation conditions Limited to few microalgae species due to extreme conditions High-contamination risk
Closed cultivation systems		
Tubular PBR	High S/V ratio good mass transfer, photosynthetic efficiency and biomass productivity Suitable for outdoor cultures Good biomass productivities Impact on cultivation conditions (pH, temperature, nutrients)	More expansive than open systems Increased need of cleaning through biofouling Requires large land space Possible formation of gradients due to inhomogeneous mixing: pH, O_2, and CO_2

(continued)

Table 10.1 (continued)

Production system	Advantages	Limitations
Flat plate PBR	High S/V ratio high mass transfer, photosynthetic efficiency and biomass productivities Sterilizable Suitable for indoor and outdoor cultures Impact on cultivation conditions (pH, temperature, nutrients)	More expansive than open systems Difficult scale-up Possible damage through shear forces Increased need of cleaning through biofouling Risk for photoinhibition and overheating through large illuminated surface
Fermenter-type cultivation system	Independent of climate conditions High productivities and harvesting concentrations Reduced downstream costs Control of process conditions Require low amount of land Suitable for indoor and cGMP cultures Scalable process strategies Easy to sterilize No energy for light required	High demand of O_2 High investment costs Sophisticated substrate feed control Expensive carbon source and special ingredients (vitamins amino acids) Risk for contamination through organic carbon source Formation of gradients Osmotic stress

exchanger) or two-phase closed bioreactors (continuous combined gas mass transfer). The usage of closed PBRs instead of open cultivation systems comprises important advantages. One advantage is that the construction can be adapted to the installation site because there is a variety of design and material (roofs, facades, industrial parks, rural areas) options. Another important benefit is the possibility to cultivate a wider range of microalgae in the closed design than in open ponds. Therefore, the contamination risk is reduced, and moderate culture media are applicable. Furthermore, it is possible to control important cultivation condition like pH, temperature, and concentrations of nutrient (phosphor, nitrogen, iron) to a certain degree. As a result of all listed advantages, higher productivities and final biomass densities can be obtained through the cultivation of microalgae in closed PBRs. Significant disadvantages are the limited scalability, which usually requires increasing the number of modules, and a high-energy demand. Thereby, the cultivation of microalgae in PBRs focuses on the production of high value products for cosmetics, food and feed for humans and animals(Acién Fernández et al. 2013; Zittelli et al. 2013).

Translucent *fermenter-type reactors* (FTR) have a major intrinsic disadvantage for phototrophic cultivations: The S/V ratio and consequently the sunlight harvesting efficiency are low (like in horizontal column PBRs). One possibility to overcome this is to use sophisticated systems of internal illumination (e.g., fluorescent lamps). The main use of fermenter reactors is for cultivating microalgae under heterotrophic conditions. A heterotrophic organism requires energy-rich complex organic compounds of nitrogen and carbon (obtained from autotrophic organisms) for metabolic synthesis. In this process microalgae are grown on well-soluble and distributable organic carbon and energy sources like glucose, glycerol or acetate in stirred fermenters out of stainless steel (Brennan and Owende 2010). The scalable fermentation technology has been studied extensively especially for bacteria and yeasts (da Silva und Reis 2015). Fermenters are characterized through high productivities and cell concentrations, a high level of automation and growth control (substrates, temperature, pH), and small S/V ratios. Therefore, heterotrophic microalgae plants need less land and provide lower investment and harvesting costs compared to phototrophic cultivation systems. Besides, heterotrophic cultivation can run over the whole year with constant productivities since it is independent of sunlight and

climate conditions. But the heterotrophic cultivation of microalgae also has several major limitations: Only few microalgae species can be cultivated under heterotrophic conditions; the process requires much energy and expensive organic carbon sources and other ingredients (vitamins, amino acids); an enhanced risk of contamination due to the organic carbon source and the inability to produce light-induced metabolites (e.g., pigments, Perez-Garcia et al. 2011).

Mixotrophic cultivation, a combination of phototrophic and heterotrophic cultivation with light and an energy-rich organic carbon source, is a possibility to link the benefits of both microalgae cultivation methods. In contrast to the single-step mixotrophic cultivation process in PBRs, the multi-step cultivation process enables the independent optimization of the individual, sequential cultivation steps (Ogbonna et al. 1997). Therefore, it is possible to cultivate microalgae under optimally controlled conditions with high mass transfer and volumetric productivities up to very high biomass density in fermenters, and to develop products of interest (especially pigments) after dilution and transfer in phototrophic PBRs. But there is also a limited number of microalgae species that switch between heterotrophic and phototrophic conditions.

The choice of the most suitable reactor system depends on the cultivated microalgae species, the location, and the products of interest. Consequently, there will be no unique design since it is a function of cultivation process parameters. Actually, all reactor types described here with their advantages and limitations summarized in ◘ Table 10.1 are applied in the global cultivation of microalgae and are therefore relevant for the prospective large-scale production of microalgae-based products (Acién Fernández et al. 2013).

10.2.2 Artificially Illuminated Microalgae Cultivation

The use of artificially illuminated photobioreactors offers the possibility of year-round stable production of microalgae biomass. In addition, the improved process control makes it possible to influence the composition of the biomass via the cultivation conditions such as the amount of light per cell/biomass or the light intensity. The enormous technical progress made in the field of LED technology in recent years is also supporting the development of artificially illuminated cultivation systems for microalgae.

The flat-panel-airlift-photobioreactor (FPA-PBR) (◘ Fig. 10.3) is pneumatically mixed and is designed to distribute the light evenly between the cells of the culture. This result in a high light yield and a homogeneous content profile of the biomass produced. With artificial lighting, it is also possible to illuminate the FPA reactor from both sides. This double-sided illumination can further increase the light yield and biomass productivity.

Standardized cultivation processes are being developed at the Fraunhofer IGB for cultivation in FPA PBRs. The cultivation conditions (e.g., nutrient supply or amount of light per cell) are specifically adapted to influence the composition of the biomass and thus produce biomass with a desired ingredient profile ("tailored production"). The FPA-



◘ **Fig. 10.3** Side view of a flat-panel-airlift-photobioreactor illuminated by blue and red LEDs from both sides (FPA-PBR) (© Mina.Blue.22 licensed under CC BY 4.0. ► https://creativecommons.org/licenses/by/4.0/)

PBRs are equipped with a control system and various sensors, which allow automation of the developed processes. Automation also helps to ensure stable processes and product quality.

The Fraunhofer IGB is also working on scaling up reactor technology (Fig. 10.4). These allow the production of up to 1 kg of dry biomass per day on a small footprint. Further scaling for industrial use is currently in progress. The scaled reactor systems are employed for the integration of algae cultivation with other processes. One such integration involves the utilization of CO_2 derived directly from industrial point sources, such as CO_2-rich exhaust gases, for cultivation purposes. The reactors are equipped with offgas recirculation for this purpose, which increases CO_2 utilization to over 90%. The use of nutrient-rich wastewater can also be implemented on site. In addition to automation, the stacked cultivation modules are equipped with internet-based remote monitoring and control, which considerably simplifies on-site production. Furthermore, these stacked modules have already been installed in overseas containers, which facilitate transportation and installation at industrial sites.

10.2.3 Processing of Microalgae-Based Biomass—Downstream Processing

The typical process for the treatment of microalgae biomass is composed of the following stages: harvesting and dewatering, cell disruption, drying and isolation of the product. Figure 10.5 shows an example of process flowcharts.

For *harvesting and enrichment (dewatering) of the biomass*, the fluid–solid separation process can be run in a single stage or in a combination of different methods (multistage). A general schematic overview of the stepwise separation and drying process of microalgae based biomass with typically achieved biomass concentration and physical state is illustrated in Fig. 10.6.

Coagulation and flocculation are methods for the pre-treatment or conditioning of fluid harvested microalgae cultures. They are based

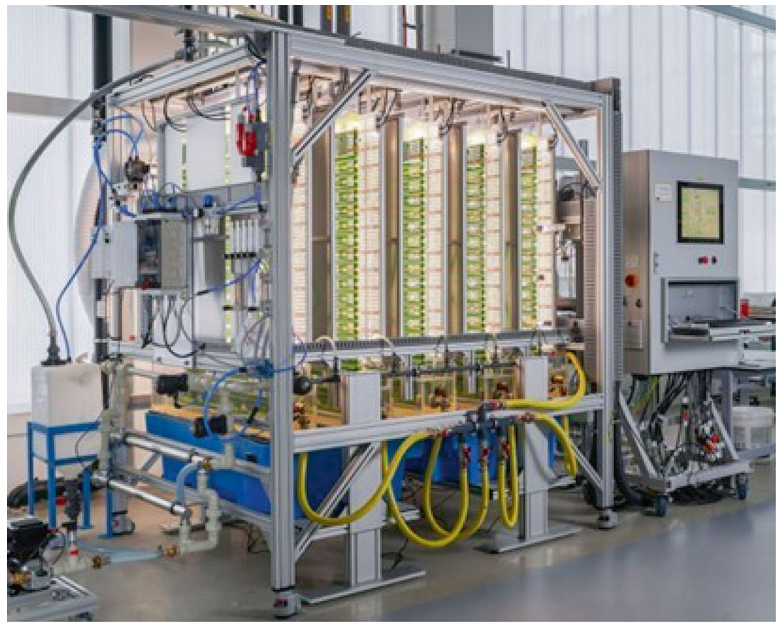


Fig. 10.4 In the SmartBioH_2 demonstration plant, microalgae of the species *Chlorella sorokiniana* are cultivated in five flat-panel-airlift-photobioreactors illuminated both sides with LEDs. (© Fraunhofer IGB)

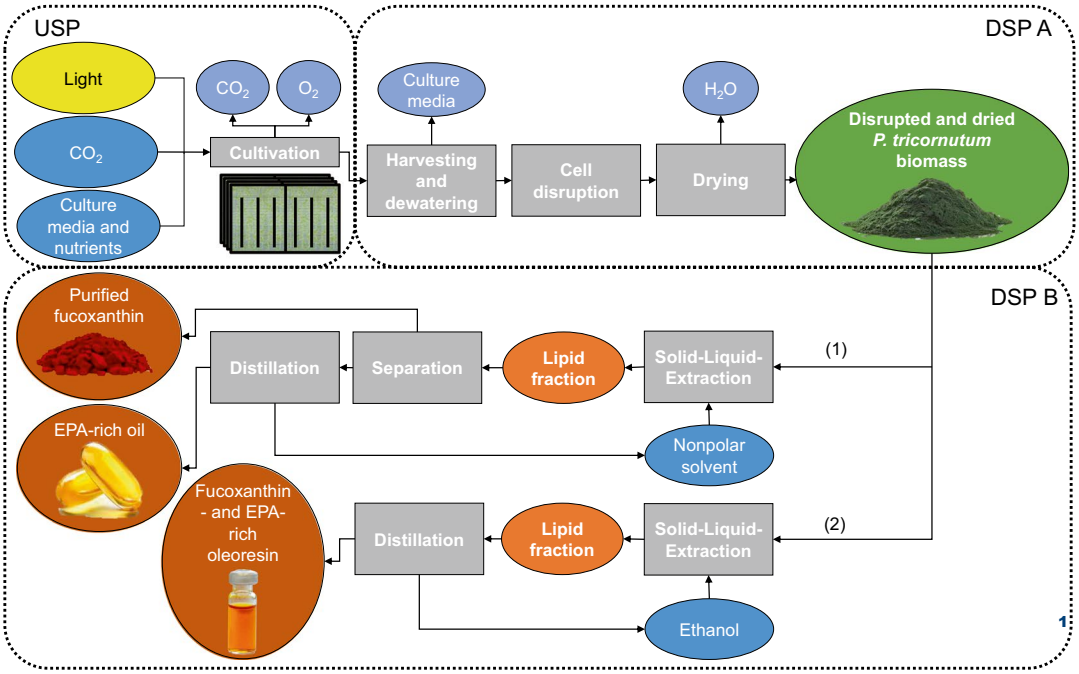


Fig. 10.5 Flow chart illustrating the production process of *Phaeodactylum tricornutum* biomass in flat-panel-airlift-photobioreactors (FPA-PBRs). Depending on the solvent, it is possible to obtain separately a crystalline fucoxanthin and eicosapentaenoic acid-rich (EPA) oil or a fucoxanthin- and EPA-rich oleoresin. The process is divided into upstream process (USP), and downstream processes (DSP) A and B. DSP B (1) and (2) differ in the solvent used in the process. EPA = eicosapentaenoic acid. (Based on Weickert et al. (2023))



Fig. 10.6 Schematic flow diagram for the stepwise process of dehydration of microalgae based biomass with typically achieved biomass concentration and physical state. (Based on Pahl et al. (2013))

on destabilization and aggregation of the microalgae cells so that the cells can be form larger flocs (Pahl et al. 2013; Fasaei et al. 2018). Coagulation involves the addition of one or more chemical coagulant and is based on the interaction between the negatively charged microalgae cell surface (mainly carboxylic acid groups), the coagulant, and any coagulant aids. Flocculation includes the aggregation of destabilized particles, and the precipitation products formed by one or more coagulants into larger particles (Pahl et al. 2013). The most used organic and biodegradable bio-flocculant is an edible non-toxic polymer of acetylglucosamine named chitosan. Also, different strains of bacteria, fungi or other spontaneously flocculating microalgae species can be used as bio-flocculants (Molina Grima et al. 2013). Auto-flocculation of microalgae appears spontaneous at reduced metabolic activity under darkness, at high pH values (pH 8–12) due to the precipitation of carbonate or other hydroxides or very low pH values (pH 4, Muylaert et al. 2017). Another method is the flocculation by acoustic waves (Pahl et al. 2013). *Sedimentation* takes place, when the density of particles is higher than that of the culture medium (Molina Grima et al. 2013). Inside optional gravity thickeners, lamella separators or other sedimentation

tanks higher density particles of a readily flocculated suspension settle out of the liquid by sedimentation to obtain a concentrated suspension of microalgae biomass (Pahl et al. 2013; Muylaert et al. 2017).

The most employed techniques are *filtration and centrifugation*, which are applied directly after harvesting the microalgae culture. The implementation of a pre-treatment step has been demonstrated to enhance the efficacy of the processes. Filtration is a mechanical or physical single-step harvesting process to separate microalgae biomass into a cake or concentrated slurry by a filtration media (permeable separator) from water or cultivation medium under gravity, pressure, or vacuum (Pahl et al. 2013; Muylaert et al. 2017; Fasaei et al. 2018). Depending on the pore size of the permeable membrane, macrofiltration, microfiltration, and ultrafiltration are distinguished (Molina Grima et al. 2013). Centrifugation is high-rate sedimentation by enhanced gravitational force due to centrifugal forces. It is the most used harvesting technology for microalgae biomass. This technique can be used directly after harvesting, but also after an earlier filtration step. There are five types of industrial scales centrifuges: disc stack centrifuges, perforated basket centrifuges, imperforated basket centrifuges, decanters (or scroll centrifuges) and hydrocyclones (Fasaei et al. 2018; Pahl et al. 2013; Barros et al. 2015; Gerardo et al. 2015).

Cell disruption of microalgae is necessary for the extraction of single or multiple compounds. It is also needed to increase the bioavailability of compounds like fatty acids or proteins for human and animal consumption. There are two main groups of cell disruption technologies: physical-mechanical and chemical, biological or non-mechanical technologies. The choice and effectiveness of the optimal method depends on the microalgae cell wall structure, the composition of the cultivation medium, the cultivation conditions (optimal or nutrient depletion) and on the final product of interest. Physical-mechanical are the most used methods for cell disruption. They are characterized by lower contamination risks due to the omission of chemical or biological additives and by a lower dependency on the choice of microalgae species. Bead milling is used in many branches of industry for grinding, lysing and homogenization of biomass based on solid-shear forces. It is based on the mechanical disruption of cells by the kinetic energy of colliding beads (glass, ceramic, plastic, or steel). Other developed methods for physical-mechanical cell disruption are high-pressure homogenization (HPH), high-speed homogenization (HSH), the utilization of microwaves, ultrasonication, and pulsed electric field treatment (PEF). For chemical cell disruption, there is a large variety of chemical compounds that can be used for cell disruption, such as antibiotics, chelating agents, chaotropes, detergents, solvents, oxidizing agents, acids, and alkali, ionic liquids and supercritical fluids. The effectiveness of the disruption process is influenced by the concentration of the used compound, temperature, pH, salt content, incubation time, biomass concentration and of course by the microalgae species of interest and on the cell wall composition. Supercritical fluids exhibit properties of gases and liquids. Primarily, this method is used for the extraction of microalgae-based lipids and pigments, manly with CO_2. But it is also a possible method for the disruption of microalgae cells. Enzymes can naturally convert carbohydrates into monomeric sugars or proteins into amino acids for an effective and selective disruption of microalgae cell walls. The main enzymes used are cellulases, glycosidases, amylases, proteases, xylanases, peptidases, and lipases, actually, for the extraction of microalgae-based lipids and the conversion of biomass into biogas (Günerken et al. 2015; D'Hondt et al. 2017; Molina Grima et al. 2013).

After the harvesting and enrichment of microalgae biomass up to 15–25% dry matter (50- to 200-fold increase in biomass density, see Fig. 10.5), the water content in wet paste remains still up to 75–85%. With the focus on the production of food and feed, fast and gentle drying to reduce the water content to about 5% to extend the shelf life and trans-

port weight of the harvested biomass is essential (Fasaei et al. 2018; Molina Grima et al. 2013).

The most used method for industrial scale *dehydration* of microalgae biomass is spray drying. This method is based on the fine atomization of liquids, emulsions, or slurry by pressure, centrifugal atomizers, or gas–liquid jets, which are continuously heated up by hot air in a large chamber (1–10 m diameter). In drum drying, hot steam heats the microalgae paste or slurry that is distributed over a rotating drum. By creating a vacuum, the performance of the process can be increased (Fasaei et al. 2018). Freeze-drying is the gentlest dewatering technology for microalgae as it maintains the structure of chemical ingredients and simultaneously facilitates cell disruption. Through the lyophilisation of microalgae biomass, it is possible to preserve pigments and proteins with minimal losses. Less commonly used industrial methods for drying microalgae biomass are due to high qualitative loss rates sun drying, hot air and solar drying. These methods are predominantly used for the production of microalgae-based biofuels or for the purification of waste waters (Chen et al. 2015).

There are two main principal methods for the *isolation* of microalgae-based products: *extraction and adsorption*. The organic solvent extraction is the most common used method. The process is for transporting materials from one phase to another for the purpose of separating one or more mixtures. The most commonly used solvents for the extraction of lipids are chloroform, methanol, n-hexane, propan-2-ol or other solvent mixtures. Depending on the polarity of the lipids to be extracted, the appropriate mixture must be selected. A previous dehydration step is necessary in each case (Ventura et al. 2017; Cuellar-Bermudez et al. 2015; Molina Grima et al. 2013). Pigments like carotenoids or chlorophyll and polysaccharide as well as lipids (see Fig. 10.7) are mainly extracted by solvent precipitation methods with cationic surfactants (mainly polysaccharides), organic solvents such as ethanol, acetone, some ether or a combination of these solvents in different proportions. Solid-liquid extraction methods (SLE) with or without mechanical processes associated such as Soxhlet extraction, ultrasonic-, microwave-, PEF-, or supercritical fluid-assisted extraction are frequently used methods for the extraction of pigments, in which solvents are added sepa-



Fig. 10.7 Fucoxanthin powder and omega-3 fatty acid eicosapentaenoic acid-rich oil in a small glass vial from *Phaeodactylum tricornutum*. (© Fraunhofer IGB)

rately or in sequential steps directly to the biomass (Ventura et al. 2017). Pressurized liquid extraction (or subcritical fluid extraction) is based on using pressurized solvents at high temperatures. If the solvent is water, this technique is also called subcritical water extraction. The pressure build-up results in increasing solvent temperatures without evaporation (maintained in the liquid state). This improves the extraction efficiency of the process by decreasing solvent volumes and process time due to an enhanced mass-transfer rate, an increased analyte solubility, and decreased solvent viscosity and surface tension (Herrero et al. 2015). Supercritical fluid extraction, like supercritical CO_2 ($scCO_2$) extraction is a cell disruption and also an extraction method (Cuellar-Bermudez et al. 2015). Due to increased pressure and heating above the critical point, CO_2 exhibits the properties of fluid solvents. This can create mild process conditions for isolation of microalgae-based extracts (Elst et al. 2018). This enables further processing of the biomass after extraction of lipids and pigments, for example, to obtain proteins and carbohydrates. This method is non-toxic, non-flammable, volatile, and easy to handle. In addition, this process is highly selective and can be adapted to different pressures and temperatures. Other less used methods are ionic liquid extraction. With an expanded bed *adsorption* (EBA) process, microalgae biomass flows upwards through a column filled with expanded and stable (with pH buffer) absorbent particles (e.g., anion exchanger diethylaminomethyl, DEAE). The dissolved substance of interest binds to the absorbent particles in the bed, while the remaining fluid biomass flows unhindered through it. After several washing steps, the bound molecules can be dissolved using pH buffers. This technique is used for the separation of proteins from yeasts and bacteria and has already been successfully integrated into the production of microalgae-based proteins (Molina Grima et al., 2013). This method is scalable and free of toxic solvents and therefore, enables highly purified fractions to be obtained under mild and non-denaturing conditions (Schwenzfeier 2013).

There are many applicable technologies for the *purification* of microalgae-based molecules such as chromatography, ultrafiltration, or electrophoresis. Chromatography is the most frequently used technique. This is based on the variety of available physicochemical interactions like gel filtration, ion exchange, affinity, reverse phase, and hydrophobic chromatography (Molina Grima et al. 2013).

10.2.3.1 Biorefinery Concept

The biorefinery concept is defined as a facility for the conversion of biomass into a variety of bio-based products like food, feed, biofuels and other chemicals (Bastiaens et al. 2017) (see Sect. ► 17.1). In the context of the bioeconomy, algae biomass needs to be utilized as holistically and efficiently as possible. Although microalgae can be used as whole cells for nutritional purposes, it is often worth fractionating the different constituents to add value to the biomass and thereby vindicate comparatively high production costs. For an economically feasible microalgae based production process, it is necessary to obtain primarily the most valuable (with regard to the return on investment) product such as pigments (astaxanthin, β-carotene, and phycocyanin) or PUFAs (polyunsaturated fatty acid) as a dietary supplement or as ingredients for the food and cosmetic industry, and secondarily a multitude of different types of extracts (Rösch et al. 2018; Gifuni et al. 2018; Chew et al. 2017). For this purpose, the parameters for cell disruption and extraction must be carefully adjusted depending on the composition of the ingredients and for each individual microalgae strain. The separation of lipids (e.g., fatty acids and carotenoids) from microalgae proteins is an approach to obtain several products from one cultivated biomass. This can be realized by cascaded extraction.

> ***Cascaded extraction*** is a combination of multiple extraction steps in order to extract multiple products while avoiding the degeneration of molecules and organic compounds within each fraction.

The challenge of cascading biorefinery approaches for algae biomass valorization is to identify and integrate novel mild disruption and extraction processes (depending on the microalgae species and products of interest) to preserve valuable secondary ingredients. In recent years, the focus has been on the extraction of microalgae-based lipids to produce biofuels. These scenarios were not economically viable due to the high cultivation and processing costs and the low price of competing fossil energy sources (Lam et al. 2018; Chew et al. 2017). The focus on the lipid fraction for energy applications has led to the use of aggressive digestion and extraction processes that severely compromise the quality of the residual biomass. Another reason is high processing costs for low-value secondary products due to the high cost of removing solvents or absorbents and drying, as well as the lack of approval for novel food and feed ingredients in the European Union (Enzing et al. 2014; Bastiaens et al. 2017; Lam et al. 2018).

Biorefinery concepts for food and feed production achieve lower non-renewable energy consumption (NREU) and greenhouse gas emissions than pure energetic utilization (Posada et al. 2016). The production of low-value and high-volume applications should therefore not be the focus of attention, but it also offers the possibility of utilizing residual biomass.

One challenge to realize microalgae biorefinery concepts is to reduce resource demands like phosphate, nitrogen, and CO_2. In order to achieve this, nutrient cycles must be closed, CO_2 of incineration plants or other CO_2-rich exhaust gases, and available organic waste streams from food industry and communities, agricultural activities, and digestate from biogas plant or wastewater treatment instead of using chemical fertilizers should be integrated in biorefinery concepts (Shurtz et al. 2017; Rösch et al. 2018). Fresh water demand can be reduced by closing water cycles through the recycling of water from downstream processes (Rösch et al. 2018).

Questions

1. What are the differences between heterotrophic, mixotrophic and photoautotrophic growth?
2. Outline and describe a possible process from cultivation to processing of microalgae biomass.
3. Which criteria have to be met for a microalgae reactor system to achieve high biomass productivity as well as energy efficiency?
4. What are the main challenges concerning cascaded utilization of microalgae biomass?

Answers

1. The differences between heterotrophic, mixotrophic, and photoautotrophic growth are:
   (a) Heterotrophic growth: Microalgae depend on organic carbon sources, such as glucose or glycerol, as their energy source. They are cultivated in opaque fermenters without light. This method ensures high productivities and independence from sunlight but is energy-intensive and limited to specific species.
   (b) Mixotrophic growth: This method combines light (like in phototrophic systems) and organic carbon sources. It leverages the advantages of both phototrophic and heterotrophic methods, allowing higher biomass productivity. However, only a few species can switch between these growth modes.
   (c) Photoautotrophic growth: Microalgae use light as their energy source to convert CO2 into biomass via photosynthesis. This method is employed in open ponds or photobioreactors and is dependent on sunlight availability.

2. A typical microalgae biomass production process includes:
   (a) Cultivation: Microalgae are grown in open systems (e.g., raceway ponds) or closed photobioreactors (e.g., tubular or flat plate designs). Factors such as light, temperature, nutrients, and aeration are controlled to optimize growth.
   (b) Harvesting and dewatering: Biomass is concentrated through coagulation, flocculation, filtration, or centrifugation.
   (c) Cell disruption: Techniques such as bead milling or enzymatic treatments break the cell wall to release valuable compounds.
   (d) Drying: Methods like spray drying or freeze-drying are used to reduce water content for better shelf life and transportability.
   (e) Product isolation: High-value compounds (e.g., pigments, lipids) are extracted using methods like solvent extraction or supercritical CO2 extraction.
3. The following criteria have to be met for a microalgae reactor system to achieve high biomass productivity as well as energy efficiency:
   (a) Efficient light use: High surface-to-volume ratios in photobioreactors ensure sufficient light exposure for photosynthesis. Double-sided illumination further optimizes this.
   (b) Controlled environment: Parameters like pH, temperature, and nutrient concentrations must be closely monitored and adjusted.
   (c) Scalability: Systems should allow scaling without compromising productivity or energy efficiency. Stacked modules or tubular reactors are examples.
   (d) Resource integration: Utilizing CO2-rich exhaust gases and nutrient-rich wastewater enhances resource use while reducing costs.
   (e) Automation: Automated systems ensure stable processes and high-quality biomass by minimizing human error.
4. The main challenges concerning cascaded utilization of microalgae biomass?
   (a) Process integration: Identifying and implementing mild extraction techniques to preserve valuable compounds is critical but challenging.
   (b) Economic feasibility: High costs of cultivation and processing, coupled with competition from fossil-based products, make cost reduction essential.
   (c) Regulatory barriers: Lack of approvals for novel food and feed ingredients limits market potential.
   (d) Sustainability concerns: Reducing resource demands (e.g., phosphate, nitrogen, fresh water) and reusing organic waste streams are necessary for sustainable processes.

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Insects

Iris Lewandowski

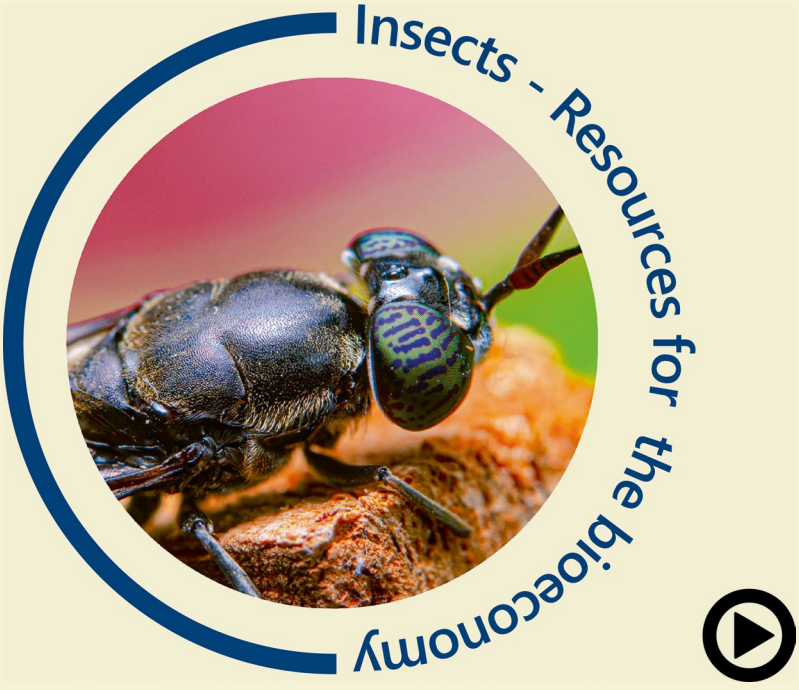


Fig. 11.0 Insects (▶ https://doi.org/10.1007/000-htp)

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Insects have traditionally been used as food and feed, and they also provide indispensable ecosystem services such as pollination and genetic diversity. This chapter gives an overview of the use of insects as food and feed and for diverse other applications, as well as the methods used to rear insects. Most edible insects are harvested from the wild, but there are also semi-domestication and farming methods. Some examples of insect farming and insect biorefineries are presented.

Learning Objectives

After studying this chapter, you will…

- …be able to describe the different ways in which insects are obtained and reared (see ► Sects. 11.5 and 11.6)
- …be able to discuss the potential of insects in a growing bioeconomy (see ► Sects. 11.1, 11.2, 11.3, 11.4, and 11.7).

11

Insects account for more than half of all identified species in the animal kingdom and contribute significantly to the Earth's biodiversity. Five million insect species have been described, of which 40% are beetles (Coleoptera), 17% butterflies and moths (Lepidoptera), 13–14% ants, bees and wasps (Hymenoptera), 10% flies (Diptera) and true bugs (Hemiptera), and 2.5% grasshoppers, locusts and crickets (Orthoptera). Most edible insects are included in these six orders (Turan et al. 2024).

11.1 Insects as Food

More than 2300 insect species, from both terrestrial and aquatic environments, have been reported as edible (Tang et al. 2019). Today, insects are mainly eaten in tropical and subtropical regions. Tropical insects are large in size, making them easy to harvest, and they cost poor rural communities less than animal protein, thus avoiding many cases of malnutrition (Govorushko 2019). In temperate regions, only China, Japan, and Mexico practice entomophagy (the consumption of insects) on a larger scale (Govorushko 2019).

Insects are a rich source of animal protein at all their life stages, with crude protein contents ranging from 33% to 66% and a good combination of essential amino acids. They can even contain more protein than conventional meat (Tang et al. 2019). Depending on their developmental stage, insects can also contain fats in the range of 6–70% of dry weight, with larvae providing the most favorable oils and fatty acids (Tang et al. 2019). Edible insects can be a good source not only of proteins and fats, but also of vitamins and minerals. An overview of the nutritional value of insects can be found in Tang et al. (2019).

As a food source, insects thus have the advantage of being cheaper than meat, while containing the same nutrients. Their life cycle is short and rearing insects does not require high start-up capital (Tang et al. 2019). Insect farming requires little space and can be performed in a water- und nutrient-efficient manner. Given the increasing pressure on limited agricultural land, they could therefore become an important alternative source of protein-rich food with high nutritional value.

Crickets are among the most commonly eaten insects. Other relevant edible insects include the larvae of the mopane caterpillar, which contain 64% protein, and the palm weevil, both of which are widely consumed in southern Africa. In Asia, the silkworm has traditionally been domesticated as food and for silk production. The production of yellow mealworm larvae has been industrialized on account of the larvae's vitality. Giant water bugs, ants, termites, mealworms, butterflies, honeybees, cockroaches, and the housefly or black soldier fly are also among the most commonly used edible insect species. 88% of edible insects are terrestrial and 12% aquatic (Turan et al. 2024). Edible insects are consumed at all their life stages.

11.2 Insects as Feed

Insects are already used as feed for livestock, poultry, and aquaculture (see ► Sect. 9.1) and are expected to become more relevant in the future because they are rich in protein and essential nutrients, can meet the increasing

demand for feed, and can also replace traditional feedstuffs such as fishmeal and soybean meal.

As many fish species feed on insects, using insect feed in aquaculture is a natural extension. The larvae of the black soldier fly are already used to feed rainbow trout and blue tilapia (Govorushko 2019).

In many countries, poultry is also already fed on the larvae of the common housefly. Other insects that could potentially be used as poultry feed include grasshoppers, crickets, cockroaches, and termites (Govorushko 2019). For this purpose, insects could be harvested from agricultural pests, which would help to reduce pest pressure while providing low-cost feed.

Insects are already farmed for pet food production, for example, dog food made from black soldier fly larvae. Cats and companion birds, many of which are entomophagous, could also be fed insects.

11.3 Other Insect Products

In addition to food and feed, there are many other potential applications for insect products:

- There is a long tradition of silkworm domestication, especially in Asia. The main product is *silk*, but silkworms are also used as food. *Silk proteins* can be extracted from silkworms and used in skin and hair care products for their moisturizing and strengthening properties. Insect silk may also have potential uses in textiles and medical sutures on account of its strength and biocompatibility.
- *Carmine*, a commonly used natural colorant, is obtained from *Dactylopius coccus* and used as a food additive, in cosmetics, and in clothing.
- The exoskeleton of adult insects contains *chitin*, from which *chitosan* can be extracted. Chitosan is used in wound care products, drug delivery systems, and water purification. Chitin and chitosan can also be used to produce biodegradable plastics.
- More than 400 kinds of *antibacterial substances* have been extracted from insects. Certain insects produce peptides with strong antimicrobial properties that are useful in the development of new antibiotics (Tang et al. 2019).
- *Shellac* or lac resin, is obtained from the secretions of the tiny female lac insect, *Laccifer lacca*. It is produced mainly in India and used in waxes for coating fruits, in the printing and adhesive industries, in the pharmaceutical industry, in sealing wax and adhesives for optical instruments, and in woodworking.
- *Insect oils*, extracted from insects such as mealworms, are rich in essential fatty acids that are beneficial for skin hydration and repair.
- Several companies produce *organic fertilizers* from black soldier fly larvae frass. Vermicompost is the product of the decomposition process of organic materials and wastes using various worm species, usually red wigglers, white worms, and other earthworms. It is used as a growing substrate for various crops, for example, in urban gardening (see ► Chap. 7).

11.4 Additional Functions of Insects

Probably the most valuable function of insects in agricultural production is pollination. Many fruit-bearing trees and shrubs, and also agricultural crops, perform entomophily, a form of plant pollination in which pollen is dispersed by insects, particularly bees, butterflies, flies, and beetles. Lippert et al. (2021) estimate the value of short-term global pollination services at the range midpoint of USD 1 trillion.

With regard to the services provided by insects, Lippert et al. (2021) write "...besides pollination of commercial crops, there are several other regulating and supporting ecosystem services linked to pollinating insects, such as their contribution to biological con-

trol or their share in the preservation of genetic diversity. Also, cultural ecosystem services providing spiritual, aesthetic, and arts inspiring benefits are likely to depreciate with a decline in pollinator incidence."

Biological control refers to the use of insects for pest control in agricultural production. Two examples are the deployment of ladybirds in greenhouses to protect the vegetables from being sucked by aphids, and parasitic wasps that lay their eggs on pests, such as aphids, whiteflies, leaf miners, and caterpillars.

The provision of honey by bees is another very valuable service, and, as reported by Phiri et al. (2022), global honey production is increasing. Traditionally, honey has been used as a sweet and a sweetener, but also as a medicine. Beeswax, used by beekeepers to make foundation sheets, is also used in more than 300 other applications, including in the manufacture of cosmetics, pharmaceuticals, candles, electronic components, polishes, and specialized industrial lubricants (Phiri et al. 2022).

11.5 Insect Rearing

More than 90% of the insects consumed worldwide are harvested from nature. According to Govorushko (2019), there are three ways to obtain insects:

- Wild harvesting, which provides 92% of edible insects.
- Semi-domestication, which provides 6% of edible insects.
- Farming, which provides 2% of edible insects.

Wild harvesting is the most traditional, but also most labor-intensive method of obtaining insects. Semi-domestication requires a suitable host plant, and edible insects are not isolated from wild populations. Ideally, semi-domesticated insects are large in size, have short reproductive cycles, form swarms, and have a high nutritional value. Examples of semi-domesticated insects include palm weevils, which are reared in Central and South America, Africa and Southeast Asia.

Farming allows insects to be bred in controlled conditions. The most important abiotic factors in insect rearing are temperature (20–35 °C) and humidity (55–77%). To create optimal growth conditions, the insect larvae are protected from drought, heat, predators, and diseases by simply covering them with branches, leaves, and shade houses or by rearing them indoors. The insects are cultivated in facilities that isolate them from their natural populations. The advantage is that insects are easier to produce than other protein sources because they have a shorter life cycle and require a smaller rearing area (Turan et al. 2024).

The Feed Conversion Ratio (FCR) is the amount of feed in kg required to achieve a weight increase of 1 kg in the production animal, both expressed in dry matter (DM). The FCR of insects depends on the species and its diet. In a feeding study with diets composed of by-products of food manufacturing, Oonincx et al. (2015) found the FCR to be higher for Argentine cockroaches and black soldier flies than for yellow mealworm and house crickets. The first two insects were considered for animal feed and the latter two for human consumption. The best FCR was found for insects fed a high-protein, high-fat diet. Here, the black soldier fly achieved an FCR of 1.4, the Argentine cockroach 1.7, the yellow mealworm 3.8 and the house cricket 4.5 (Oonincx et al. 2015). This shows that the two species suitable for human consumption convert feed into consumable food as efficiently as poultry, more efficiently than pork, and more than four times as efficiently as grain-fed beef. In contrast to conventional animal production, where growth rate is mainly determined by the energy content of the feed, the type of protein and its composition are more relevant for insects, because they do not need to maintain their body temperature at a constant level. With a suitable diet, insects use nitrogen more efficiently than conventional production animals and their nutritional value is influenced by the composition of their diet (Oonincx et al. 2015).

11.6 Insect Farms

In India and Southeast Asia, there are many relatively small-scale, family-run insect farms (Tang et al. 2019).

The largest insect factory (insect farm and processing plant) in the world is the company ► Protix, which opened in the Netherlands in June 2019. It uses organic waste from industry to feed black soldier fly larvae, which in turn are used as feed for livestock, aquaculture, and pets.

In these large farms, insects are bred exclusively inside buildings where all factors involved in rearing can be precisely controlled. This means that temperature, humidity, brightness of artificial light sources, volume of the space provided, and other factors can be closely monitored and adapted to the insects' needs. Many steps in the farms can be automated. Sensors control factors such as temperature and humidity and optimize them automatically.

In his video on "► Insect farming for feed and food," Dr. Lars-Henrik Lau Heckmann provides in-depth insights into processes, business concepts and markets of insect farming.

11.7 Insect Biorefineries

Insects are of interest for biorefining as they can make use of organic wastes and residue streams and be further processed into various products.

The insect farm ► ILLUCENS rears black soldier larvae on upcycled organic side-streams and further processes them into proteins and lipids for animal feed, dried larvae for poultry, and puree for pet food. Soil enhancers are made from the side products of these processes.

► InBiRa, an insect-based biorefinery, processes food waste and residue streams into a feed suitable for black soldier fly larvae. In the larvae biorefinery process, fats and proteins are separated. The fats are further processed into fuels and cleaning agents, while the proteins are converted into foils and adhesives or processed into animal fodder. The residues from the biorefinery process are used to produce chitosan or bio-based fertilizer.

Questions

1. How are insects harvested?
2. Which role do insects play in the bioeconomy?
3. Give three examples of different insect-based products.

Answers

1. More than 90% of insects are harvested from the wild and so provide a cheap but nutritious food. Semi-domestication takes place outdoors and requires suitable host plants. However, collecting insects from nature is very labor-intensive. For this reason, indoor farming, which today accounts for only 2% of edible insect production, is expected to increase in future, as it allows insect production under controlled conditions and offers the potential for automatization.
2. Insects and the services they provide, such as pollination, are indispensable for agricultural production and biodiversity. Due to their high nutritional value, insects could serve as substitutes for animal meat or feed products, such as fishmeal and soybean meal. This would help meet the increasing demand for high-quality protein food for a growing population without increasing pressure on agricultural land.
3. Possible example products are: Silk/silk proteins, Carmine, Chitosan, Shellac, Feed, Organic fertilizers.

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Residual Biomass: Origins, Characteristics, Composition

Evelyn Reinmuth and Philipp Scheurich



Fig. 12.0 About ▶ Chap. 12—Residual Biomass—Origins, Characteristics, Composition (▶ https://doi.org/10.1007/000-htq)

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This chapter summarises all aspects relevant to understanding residual biomass in the context of bioeconomic processing solutions. Initially, the origin of residual biomass is discussed, starting at the farm level and extending to industrial processing. Factors influencing the quality aspects of residual biomass are key to understanding the suitability of valorisation pathways and its potential as a relevant biomass for the circular and sustainable bioeconomy. Many bio-based products are the result of a combination or integration of fractions of a raw biomass, so this chapter provides an in-depth understanding of the major and minor fractions of plant biomass and links these fractions to potential applications of high commercial interest. Different discourses allow a deep dive into relevant aspects that are key for a thorough understanding of the full valorisation potential of residual biomass.

Learning Objectives

After studying this chapter, you will…

- …be able to comment on the dynamic definition of residuals and the interdependence between the main product and the resulting residual (see Sect. 12.0).
- …be able to illustrate the difference between first stage and consecutive stage residuals by giving examples for either type (see Sect. 12.0).
- …be able to name and give examples for the different origins across which residuals may originate (see ► Sect. 12.1).
- …be able to name and explain how different factors affect the quality and valorisation potential of residuals (see ► Sect. 12.2).
- …be able to elucidate the influence of the main utilisation path on the quality and composition of the residual biomass as well as the availability of individual compounds (see ► Sects. 12.2 and 12.3).
- …be able to give examples of the most important compounds contained within different residual biomass streams (see ► Sect. 12.3).
- …be able to give examples of options for the valorisation of residuals (see ► Sect. 12.3).

So far, ► Chap. 5 has established that the bioeconomy's resource base is manifold, with bio-based resources stemming from a variety of different origins. While there are bio-based resources that are produced carefully and with a specific bioeconomic focus, a vast amount of biomass is primarily produced to serve purposes such as the provision of foods. These production activities typically create a main product as well as variable amounts of organic by-products or residual streams. Similarly, the further processing as well as the consumption of the main product also result in the formation of biomass streams, all of which typically are of no commercial use and are thus eliminated or discarded after the completion of a process (Bugge et al. 2019).

Following the logic of a circular bioeconomy as described in ► Sect. 3.3, those biomass streams that are unavoidably produced during primary production and industrial processing are referred to as *residuals or residual biomass*, and may be salvaged and valorised within high-value bioeconomic processing solutions. Note that value here does not exclusively refer to economic value but may also include e.g. the human need value. Residuals, typically, represent only a share of the biomass that constitutes the main focus of production or processing. They come into existence due to the way the main biomass was managed, harvested, or processed. For the bioeconomy, residuals represent an interesting and promising bio-based resource given the vast amount of bioeconomic processing solutions and recently developed technologies that are capable of utilising either complete residual biomass streams or some of their contained compounds to create new products including new food products.

All other discarded biomass streams, for instance those stemming from consumption of biomass (e.g. food and kitchen scraps produced at household level), which at present cannot be salvaged in qualities sufficient for

them to be valorised within high-value bioeconomic processing solutions and are therefore only suitable for low-value bioeconomic processing solutions (i.e. composting or anaerobic digestion), may be considered as *biogenic waste* (also referred to as organic waste). While waste as a term falsely implies that the biomass in question is within a state that does not allow any further conversion of the biomass, organic waste streams still represent a valuable resource for the bioeconomy. Even though they, at present, may not be converted into products of use for consumption, they still serve as valuable substrates for the production of soil amendments, fertilisers or energy via processes such as composting or anaerobic digestion.

Residual biomass streams, originate from all known agricultural systems, including forest-based agriculture, agroforestry systems or marine farming systems that purposefully cultivate food crops and non-food crops as well as from industrial processing (Castilla 2013). In contrast to purposefully produced biomass fractions, residuals serve no predetermined purpose and oftentimes do not have any or only marginal market relevance (Esteban et al. 2008). As a result, they are typically not subject to any specific quality requirements, which causes them to occur in various forms, volumes and random qualities as a consequence of the manifold array of diverse agricultural management, harvesting and processing technologies.

Residuals (also referred to as *residues, side streams, by-products* or *secondary resources*) are biomass streams which are unavoidably produced within agriculture (including landscaping and urban gardening), forestry and marine farming ecosystems as well as industrial-processing, where they do not represent the target product and may be salvaged and valorised within high-value bioeconomic processing solutions.

A ***bioeconomic processing solution*** entails a single- or multi-step valorisation process or process chain that converts a biomass substrate (e.g. a residual) into an intermediate (or more rarely, a product) and one or more consecutive stage residuals.

Even though we have defined residuals as biomass streams, which are unavoidably produced within agriculture, forestry and marine farming ecosystems (including landscaping and urban gardening) as well as industrial-processing, where they do not represent the target product and may be salvaged and valorised within high-value bioeconomic processing solutions, it is important to understand that the definition as well as the term 'residual' are dynamic. This is because the nature of a residual is determined by the current use of the main product (e.g. the harvestable part of a cultivated crop). Nature per se does not know any residuals, as all biomass fulfils a purpose within the natural cycle. Farmers as 'collaborators of nature' have become experts in using biomass through separating the parts of a crop that fulfil a certain purpose either on the farm (e.g. straw for bedding, grass cuttings for feed), for the food system, or for other commercial uses (e.g. energy or material production), from those that have no intended use within any of the aforementioned valorisation pathways and therefore remain as residuals. However, as the available valorisation pathways are not constant, but change over time, e.g. due to changes to the technology landscape as well as the social (e.g. acceptance of certain industrial practices, sustainability awareness) and political context (e.g. changes in regulations and legal frameworks), the biomass streams that remain as residuals, and therefore their definition, are in a constant state of flux.

From a bioeconomic perspective, residuals represent an interesting and promising bio-based resource given that most contain valuable (chemical) compounds that allow them

to be used to produce value-added products. The overall goal of a *sustainable circular bioeconomy* is thus to salvage these residuals and their valuable components to create as many bio-based products as needed to substitute fossil-based products.

Within the scope of a circular bioeconomy and considering the cascading use of biomass (see ▶ Sect. 3.3), residuals can be further subdivided into first-stage, consecutive-stage and final-stage residuals.

While the term *first-stage residuals* ties in with the general definition of residuals to denote all biomass that is unavoidably left behind when a certain fraction of a crop is separated to fulfil a specific use, the term *consecutive-stage residuals* denotes the biomass streams that come into existence once a first- or another consecutive stage residual stream is valorised within a bioeconomic processing solution to produce a value-added intermediate or product.

Consecutive-stage residuals are typically of lower overall quality than first-stage residuals, given that their potential for use in bioeconomic processing solutions has been affected by the processes applied to valorise the initial residual. Accordingly, they may no longer be suitable for bioeconomic processing solutions of equally high value, but only for those of lower value (Sirkin and ten Houten 1994).

In turn, *final-stage residuals* are those residuals that are at the bottom of a valorisation cascade and may no longer be valorised to produce a value-added product. Unlike linear economies, which typically consider these residuals as waste to be disposed of either by incineration or landfilling, the circular bioeconomy recognises the potential of these residuals in terms of the nitrogen, phosphorus and potassium they contain, which can be returned to the field following simple conversion processes, thereby closing existing nutrient cycles (Hamda et al. 2023).

12.1 Understanding the Origins of Residual Biomass Streams

Production activities in *agriculture, forestry and marine farming ecosystems*, which can be summarised as primary production, produce outputs that are intended for food production, material, pharmaceutical or energy use. The harvesting of these outputs and their subsequent *(industrial) processing* generate residual biomass streams. Further, the *landscaping* of nature reserves or public green spaces, such as hedges or roadside greens, managed by municipalities or farmers, produces large amounts of residual biomass. In addition to these forms of open-air agriculture, typically found in rural areas, residual biomass is also produced in urban areas as a result of *open-air rooftop agriculture or urban gardening* as well as within closed systems, such as *vertical farming or glasshouse farming systems* for horticultural production of vegetables or flowers (Castilla 2013, see ◘ Fig. 12.1).

Depending on their origin, residual biomass streams exhibit different characteristics that determine their bioeconomic valorisation potential. It is therefore crucial to gain a deeper understanding of the residual biomass' origin before subjecting it to any valorisation process. Furthermore, as the concept of a sustainable and circular bioeconomy emphasises the importance of the local sourcing of raw materials to create more resilient supply chains, it is essential to understand where residual biomass streams may occur (e.g. on the field, during processing, etc.) and to gain insight into the processes within which they are generated. Acquiring this information is the first step in establishing a value-web and helps to identify and connect all relevant actors required to transform the biomass stream into a commercially relevant stream that may be used to create a value chain for bio-based products (see ▶ Chap. 4).



Fig. 12.1 Overview of different origins of residual biomass streams

12.1.1 Residuals from Farm & Field

12.1.1.1 Residuals from Crop Production

Plant-based residuals are generated across various stages of primary production, both during and outside the vegetative phase of crops. Typically, residuals at the farm and field level are very diverse. They may occur in small to large quantities and may be mixed, plant-specific or separated by variety, depending on the size of the fields and whether the main products are produced or harvested separately. They occur mainly at an expected point in the year as seasonal residual biomass streams with expectable volumes.

During the vegetative phase (i.e. the phase when any annual or perennial plant begins to grow, forms roots or leaves, and produces its harvestable yield), residuals mainly result from *pruning*, *trimming*, or *thinning* (Prasad et al. 2017). These operations are carried out to ensure high-quality yields and to minimise the risk of products not meeting industry standards and therefore being rejected by retailers and, eventually, consumers. Thus, the residuals at this stage consist mainly of removed green material, mostly leaves or young branches, as well as unripe or damaged fruit.

At the time of harvest, residuals may comprise every part of the plant that is not purposefully harvested and therefore occurs as a harvest by-product, or that is removed in preparation for harvest (e.g. the plant material of potatoes or pumpkins is removed before harvest). Straw is the most common residual at the point of harvest. It is a by-product of cereal production and is usually baled and then stored for use in animal production.

Examples of typical residuals from crop production are:

- Unripe or damaged fruit from thinning (e.g. apples or pears)
- Leaves and young branches from thinning or pruning (e.g. of fruit trees in orchards)
- Straw from cereals (e.g., wheat, barley) and oil fruits (e.g. rapeseed)
- All kinds of residual plant material (e.g. pumpkin or melon plants)
- Sunflower heads and stems
- Vegetable leaves (e.g. salad, kale, amongst many others)
- Produce that does not meet industry standards and is therefore discarded

12.1.1.2 Residuals from Livestock Production

Residuals from livestock farming include animal excrement (i.e. liquid and solid manure), bedding material, hair, feathers, carcasses, broken eggs, spoiled or overdue feed, as well as milk or wool which must be disposed of. As with plant residues, these residues occur mainly at an expected point in the year as seasonal residual biomass streams with expectable volumes.

12.1.2 Residuals from Landscaping

Residual biomass recovered from landscaping may comprise leafy or herbaceous biomass from grasslands or peatlands that are not used as agricultural land (e.g. nature reserves), woody biomass from shrubs or trees, but also herbaceous and woody biomass from public greenery (e.g. hedges or roadside landscape elements), as well as biomass removed during the landscaping of ponds and rivers.

At the landscape level, the occurrence of residual biomass is often determined by contracting for landscaping, which adds complexity to the seasonal fluctuations. In contrast to the farm and field level, where residuals regularly occur in separate crop-, animal- or variety-specific batches, residual biomass at the landscape level predominantly occurs in a mixed form that contains leafy and woody elements from crops, shrubs and trees that have been collected simultaneously. Mixed residuals present a challenge for valorisation, as their mixed nature reduces the options for further processing (see ► Chap. 22).

Examples of typical residuals from landscaping are:

- Bulrush cuttings
- Leaves and woody cuttings from roadside greenery
- Woody cuttings from shrubs and bushes
- Grass from urban green areas

12.1.3 Residuals from Forestry

Residuals from forestry may include, for example, branches and leaves from cutting and debranching as well as bark, moss and lichen. In contrast to the farm and field level, residuals from tree harvesting often remain in the forest and are not removed from their point of origin. Unexpected residuals in forestry are woods damaged by storms or fires. In the Mediterranean area, residuals also include leaves from forest trees or shrubs.

Examples of typical residuals from forestry are:

- Residual foliage of forest trees and shrubs
- Wood damaged by storms or infestations
- Sawdust

12.1.4 Residuals from Controlled Environment Farming

Controlled environment farming comprises greenhouse and indoor vertical farming in aeroponic or other soil-based or soilless cultivation systems. Residuals from greenhouse farming may include plant material from thinning or pruning, unripe fruit or vegetables, as well as fruit or plant material removed due to pests or fungal infections. Furthermore, after a production cycle, large amounts of substrate and the remaining plants are typically removed within a short period of time. Residuals from vertical farming, in contrast, comprise root biomass from aeroponic systems, as well as substrate used in soilless cultivation systems. As opposed to open field cultivation, controlled environments are less subject to climatic influences, which causes residuals to occur all year round (Cutress 2024).

Examples of typical residuals from controlled environment farming are:

- Vegetables with shapes that do not meet industry standards or are damaged
- Plant parts from thinning

– Whole pepper, tomato or cucumber plants after harvest
– Growth substrates after harvest

12.1.5 Residuals from Marine Farming

In marine farming systems, where fish and algae are grown in open aquaculture systems, residuals are rarely generated during production, but rather during the first step of downstream processing, that is, the preparing of the produce for sale. Examples of residuals include fish scales, heads or tails, as well as mussel or lobster shells. The amount of residual biomass produced varies greatly depending on the size of the produce. For instance, the preparation of larger fish typically produces around 10–15% of the fish's weight as residual biomass, while smaller fish can produce up to 25–30% of their weight as residual biomass (Gardner Pinfold Consultants Inc. 2022).

12.1.6 Residuals from Post-harvest and Pre-processing Operations

Once harvested, produce is sorted and pre-processed to turn it into a base product for the food, feed, materials, pharmaceutical or chemical industries. The manifold processing units and preparatory processes involved may be summarised under the term post-harvest and pre-processing operations.

These operations process and transform any produce into marketable intermediates suitable for further processing by other industries or consumers, or for direct consumption. They therefore include the sorting, cleaning, washing, cutting, dehulling, sieving, milling, grinding, distilling or pressing of plant-based produce such as fruits and vegetables to obtain raw juices, purees or concentrates. For animal produce, post-harvest and pre-processing operations include slaughtering and cutting the whole carcass into fractions prepared for further processing by butchers.

> ***Post-harvest and pre-processing operations*** comprise all those unit operations carried out to pre-process and transform the produce of primary production into marketable intermediates that serve as a base for further processing by other industries or by the consumer. While the inputs, processing units and processing processes may vary depending on the type of industry for which the produce is pre-processed, the outputs are always market-ready intermediates.

Post-harvest and pre-processing facilities are typically located close to the producing farms or forests, or in some cases, are directly integrated as a processing unit. In the latter case, farms frequently operate several different pre-processing units, which generate unit-specific residuals. For instance, fruit and vegetable farms often pre-process their produce for sale in market-ready cartons. This results in residuals, including damaged fruit and vegetables as well as leafy and fibrous plant parts (e.g., outer leaves or stalks), which are removed as a service to the consumer.

At the same time, there is a well-established number of non-integrated pre-processing facilities for the food industry, which comprise mills (for cereals and oilseeds), fresh-cut centres (for vegetables and fruit), juice producers, jam makers, distillers or wineries. For the non-food and chemical sectors, where the required intermediates are platform chemicals or dried fibres, such facilities are not yet very well established. Typical processing plants in this sector are drying plants, lumber mills, but also biorefineries, which at present mainly process raw materials that are not included in the pro-

cessing of food production (e.g. stems, leaves), but may become increasingly important in the future (see Excursus 12.1).

Residual biomass streams from post-harvest and pre-processing operations may occur as seasonal or year-round residual streams, as it is the case when fruit is frozen after harvest and processed in winter, depending on the source and type of the produce.

12.1.7 Residuals from (Industrial) Processing

Industrial processing is characterised by automated production with one or more technological processing steps (in some cases including the downstream sector as an integrated pre-processing unit) that are carried out in a processing plant and may be found across all sectors, including the food, chemical or materials sectors.

During the *industrial processing of food products*, several of the intermediates produced in the downstream sector are combined to produce a single product (e.g. a food product), usually according to a recipe. Residual streams from industrial processing therefore often contain a combination of several components.

Examples of typical residuals from industrial processing are:

- Brewers' spent grain from beer production
- Discarded bread or sweet bakery products generated in large bakery plants when oven temperatures are adjusted at the start of production of a new batch or when products are burnt.

The *industrial processing of non-food products* involves processes and technologies that utilise bio-based-chemicals, physical forces or mechanical steps. In this respect, it is highly similar to the fossil-based production of non-food products. In both cases, the resulting products enter the technical cycle as described in the cradle-to-cradle concept (McDonough and Braungart 2009) and usually require technical or chemical recycling to ensure that materials can remain in the material cycle for as long as possible (see ▶ Sect. 17.1). For such products, their bio-based origin may no longer be overtly visible, and it is even more difficult to identify whether residuals have been used as feedstock for their production.

Excursus 12.1: Biorefineries with Upcycling Potential

Biorefineries and novel upcycling plants are an emerging downstream sector that handles and processes raw materials that are currently considered as residuals (e.g. stems, roots, pomaces, etc.). They help to repurpose otherwise discarded residual streams from pre-processing and turn them into basic products for the food and other industries (e.g. apricot kernels are specifically pre-processed for vegan cheese production). Key to this re-integration process is that residual streams are treated as co-products of the initial processing step and that all quality-determining measures necessary to qualify the stream as a high-quality (food) resource are taken (see ▶ Chap. 22). Biorefineries are thus a novel player in the processing industry with a significant impact on the bioeconomy (see ▶ Chap. 17). While many industries have high demands for different quality aspects of biomass, biorefineries can specialise in processing residuals as their main biomass feedstock. As such, they can simultaneously produce food and feed, as well as non-food products, in one location, while ensuring that the final residual biomass may still be returned to natural cycles (e.g. as soil nutrients).

12.2 Understanding the Influencing Factors on the Quality and Valorisation Potential of Residual Biomass

For a long time, residuals were not part of the planning of production routines in agriculture, forestry or marine ecosystems. Only after a substantial amount of time, primary producers and food and material processors found ways of dealing with the residual biomass produced within their processes. This mainly involved using these residuals to produce feed, compost or biogas, or in the worst case, landfilling or burning the residuals. Recently, bioeconomy research and bright entrepreneurs have developed new ways of valorising residuals to produce high-quality products, either by focusing on extracting specific valuable compounds or compound fractions from the residual biomass, or by developing profound solutions to convert the entire residual. As a result, residual biomass has gained increasing attention as a valuable bio-based resource for several industrial sectors and has sparked research for the development of several bioeconomic processing solutions that aim to valorise it into value-added products. However, while there are a variety of bioeconomic processing solutions, it is important to understand that the quality and valorisation potential of a residual have a significant influence on whether and how a residual may be processed, incorporated into existing manufacturing processes and ultimately converted into a product. The following sections therefore aim to provide an overview of the factors that may influence the quality and valorisation potential of residual biomass.

12.2.1 Characteristics of Residual Biomass that Affect their Quality and Valorisation Potential

In general, the quality and valorisation potential of a residual biomass stream are determined by its perishability, varying availability and compositional heterogeneity. These factors, which together with their resulting implications for logistic processes, valorisation pathways and technologies, are influenced by several factors and decisions made at different points throughout the residual biomass stream's entire life cycle (see ◘ Fig. 12.2). Aside from these aspects, additional minor determinants such as physical characteristics as well as legal and regulatory aspects may also influence the quality and valorisation potential of different residual biomass streams.

12.2.1.1 Perishability

All residual biomass streams, regardless of their origin, are characterised by a varying but significantly increased degree of perishability, which causes their handling to be more complex and delicate compared to other types of bio-based resources.

The perishability of a residual biomass stream is mainly determined by its total solids/moisture content, which determines the rate of microbial growth and the resulting degradation and thus has a significant influence on the (pre-) processing technologies required for the residual's valorisation as well as its potential for certain valorisation options. In particular, the processing of residuals into food or pharmaceutical products is often limited by microbial contaminations (see ▶ Chap. 22), which prevent their use, although the residuals would be highly suitable solely based on their composition.

For instance, high-moisture apple pomace produced during juice production, typically begins to degrade within the first hour following its generation, mainly due to its high water activity that facilitates microbial growth. Without appropriate storage (e.g. refrigeration, freezing), precise logistics and pre-processing using oven-, freeze- or spray-drying, it is currently often not possible to valorise such high-moisture residuals.

12.2.1.2 Varying Availability

All types of residuals have a temporal dimension to their availability for valorisation processes. While some occur on a regular, predictable basis, others may occur at

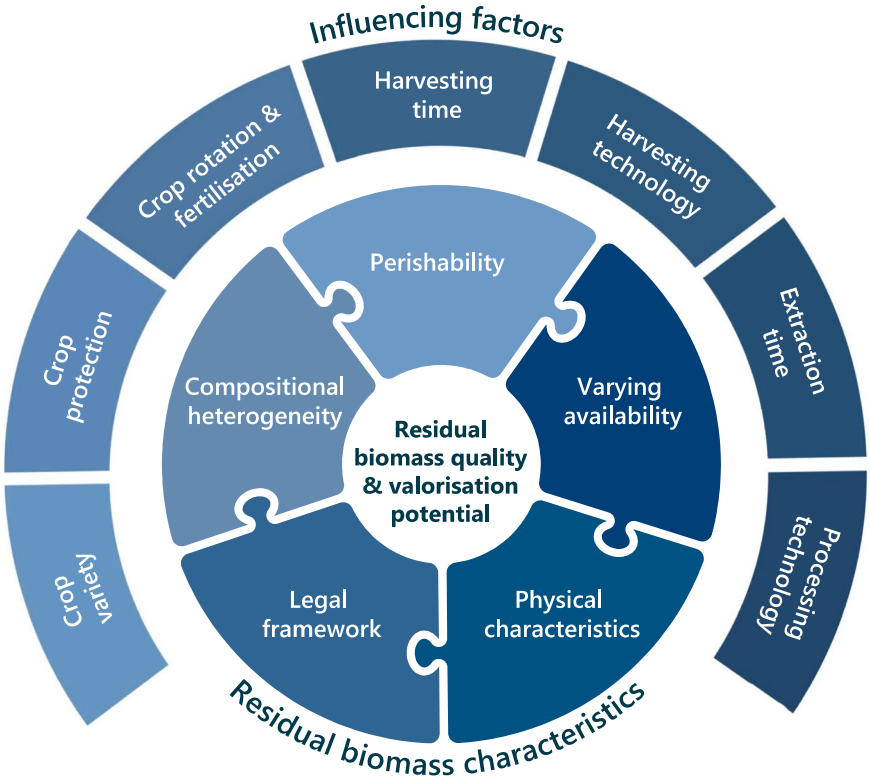


Fig. 12.2 Characteristics and factors that affect the quality and valorisation potential of residual biomass

random. This temporal dimension is most relevant to plan the logistics and processing processes for the valorisation of residuals, especially given their high perishability.

Regularly expectable residuals occur at a predictable time of the year, in predictable quantities, and in a specific location or cultivation area. Examples of these residuals and their times and places of occurrence are given in Fig. 12.3.

Irregularly occurring residuals, in contrast, represent biomass streams that occur without predictable volumes, at unspecified times and in diffuse locations. Examples of these residuals are surplus vegetables (e.g. tomatoes or pumpkins) or fruit damaged by hail.

12.2.1.3 Compositional Heterogeneity

All types of residual biomass exhibit compositional heterogeneity, resulting from various factors that affect their composition during their respective generation process within agricultural production or industrial processing. For instance, some residuals are rich in carbohydrates or proteins, while others contain high levels of fats or secondary plant compounds. These differences in residual composition directly influence their suitability for various applications as well as their value to different industrial sectors. For most residuals, compositional heterogeneity is driven by various factors, ranging from different crop varieties to management decisions within agriculture or industrial processing. These factors cause individual residual streams, and in some cases even individual batches of the same residual stream, to differ significantly in terms of their contained major and minor constituent fractions.

For the bioeconomy, the compositional heterogeneity of residuals makes their valorisation both challenging and promising, as it increases the complexity and cost of valorisa-

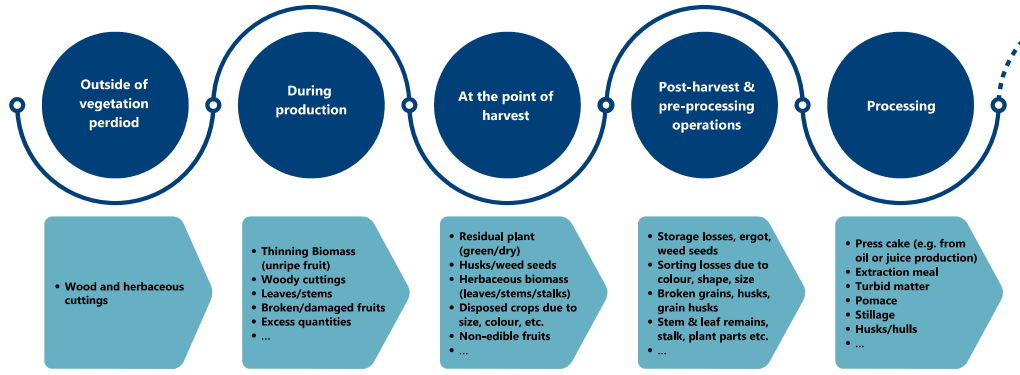


Fig. 12.3 Time of occurrence of regularly expectable residuals, for the example of plant biomass residues from the agricultural cultivation programme in Germany

tion efforts, but also offers a wide range of opportunities for sustainable valorisation and value creation.

12.2.1.4 Other Determinants

Residual quality and valorisation potential are further affected by physical characteristics such as the residual's weight, volume and aggregate state, as well as the regulatory framework governing its use for different applications. The weight, volume and aggregate state of the residual biomass stream mainly affect the residual's storage capacity as well as the logistics required to transport the residual to the processing plant. This is crucial as valorisation may only be guaranteed if appropriate logistics and storage facilities are available. At the same time, the physical characteristics may also limit the number of suitable valorisation pathways, given that certain processes and their process technologies can only deal with residuals in a certain aggregate state. For example, most carbonisation processes require dry feedstocks, whereas hydrothermal carbonisation can be applied to feedstocks with high moisture content (see ► Chap. 19).

Similarly, regulatory and legal restrictions may affect the residuals' valorisation potential and, indirectly, their quality. Throughout Europe, several pan-European and regional regulations (e.g. regarding material properties, fire safety, load-bearing capacity, water repellence or food safety) determine how residual biomass can be valorised. Typically, these regulations determine the valorisation potential of the residual biomass stream based on its origin. For example, one of the main issues in this regard arises due to waste legislation requirements, which require the residual biomass streams produced during industrial processing to be declared as waste once they leave the process. This declaration poses one of the largest obstacles to valorisation within high-value valorisation pathways as once a residual stream has been classified as waste following the European (or a national) waste directive, it can no longer be valorised within the food, pharmaceutical or any other higher-value sectors, as there are quality requirements and legal restrictions in place that rule out the use of any material that has been declared waste for the production of foods, animal feed or pharmaceutical products. As a result, several residual streams remain as waste or occur in qualities lower than possible, as there is no incentive for businesses to ensure proper pre-treatment or storage.

12.2.2 Influencing Factors that Affect the Characteristics of Residual Biomass During Crop Management

The production system determines the way in which biomass is produced and thus has a significant influence not only on the composition

and nature of the main product, but also on the residuals produced. The quality and valorisation potential of residuals is therefore determined as early as during primary production by the choice of crop management practices, including the choice of crop varieties, crop protection practices and harvest time.

12.2.2.1 Crop Variety

Different crop varieties (also referred to as cultivars or genotypes) differ in their morphological and compositional makeup, that is, they contain different concentrations of potentially valuable compounds for bio-based processing. In some cases, the wild type (i.e. the original variety of a plant as found in the wild from which other varieties have been derived through breeding) may even contain compounds or compound fractions that are not present in any of the derived varieties, making it an interesting object of study for bioeconomic endeavours. As a result, residuals derived from different varieties may differ in their composition. The choice of the variety is hence crucial for most, but especially for *drop-in valorisation routes*, i.e. valorisation routes where a (pre-processed) bio-based intermediate is used to replace a chemically identical fossil-based intermediate within an existing production process with the same characteristics (Sara et al. 2016).

12.2.2.2 Crop Protection

Crop protection measures, typically taken out to ensure high yields of primary products, may affect the composition and perishability of residuals. On the one hand, the reliance on crop protection measures may cause residuals to contain the remnants of chemical pesticides, which regularly poses an obstacle to their processing into food, pharmaceutical and cosmetic products, as well as some materials. While the main products used in food production are nowadays strictly controlled for pesticide residues, this is not the case for residuals, thus limiting their potential for valorisation. On the other hand, the avoidance of plant protection may also alter the composition of residuals as, in the absence of plant protection, plants naturally produce compounds that serve as defensive mechanisms or as signalling molecules within symbiotic interactions. In addition, the avoidance of plant protection may facilitate the assimilation of toxic compounds and contaminants from fungal, viral or bacterial plant infections. For the processing of residuals into food, pharmaceutical or cosmetic products, these unwanted compounds and contaminants may prevent the valorisation of the residuals.

12.2.2.3 Crop Rotation and Fertilisation

Like crop protection measures, fertilisation and the use of specific crop rotations play a key role in influencing the composition of residuals. Fertilisation measures may promote or inhibit the production of certain compounds within a plant. For example, overfertilisation with nitrogen has been associated with the production of undesired levels of nitrate in crop leaves and a reduced production of secondary plant metabolites such as vitamins and anthocyanins, whereas a balanced nutrient supply may favour the synthesis of the latter substances (Albornoz 2016).

Similarly, the cultivation of different plant species in crop rotations affects the plant nutrient composition of the soil, which in turn influences the availability of essential elements for subsequent crops and thus their composition. A well-designed combination of fertilisation and crop rotation is therefore essential to optimise not only the quality of the main products but also of the residuals produced.

12.2.2.4 Harvest Time & Technology

The way by which crops are harvested as well as the timing of harvesting affect the composition of residuals, their availability and their suitability for different valorisation pathways. As all other organisms, crops throughout their life-cycle are able to adapt the expression patterns of certain regions within their genome, allowing them to produce certain chemical compounds required for their respective growth stage or to adapt to external influences (e.g. heat stress proteins). As many of these chemical compounds are mobile within the plant, they may be found in different parts of the plant at different times during its growth.

► Example: Sunflower Harvest

Sunflowers are currently harvested once the entire plant, including the stalk that currently represents one of the main residuals, has completely dried out. This is done using a technology that shreds the stalk into several pieces that remain on the field. However, earlier harvesting at the point in time where the seed pod has dried out, but the stalk is still flexible, using a technology that removes the pod and then salvages the stalk by cutting it close to the ground, could make it possible to valorise the fibres and the inner mark of the stalks (Thüringer Landesanstalt für Landwirtschaft 2006; Verein Informationssystem Integrierte Pflanzenproduktion e.V. 2024). ◄

As current harvesting times and technologies are aimed at ensuring the highest quality of the main product, residuals may be obtained in compositions and quantities that are not ideal and therefore may not be suitable for all valorisation pathways, thus limiting their overall valorisation potential. In the future, biomass production aimed at a holistic bioeconomic valorisation may require a more carefully designed management of all biomass streams that can be generated from a crop. The task for the coming years will therefore be to identify the quality parameters required by the different bioeconomic valorisation pathways, to define and coordinate optimal harvesting points and technologies for the different parts of the crop, and to further develop agricultural machinery so that it may harvest the plant parts that are the focus of bioeconomic valorisation.

12.2.3 Influencing Factors that Affect the Characteristics of Residual Biomass During Downstream and Industrial Processing

Similar to the influence of crop management operations, the processes carried out during post-harvest management, pre-processing and industrial processing affect the quality and valorisation potential of residuals. These include storage conditions, (pre-)processing or extraction technologies used, as well as the chemicals and temperatures applied during these processes. At the same time, industrial processing places certain demands on the (sustainable) valorisation of residuals, which may also affect the residual's valorisation potential within various sectors.

12.2.3.1 Extraction Time

Just as the optimal harvest time is crucial to ensure high residual quantities and optimal composition for valorisation, the time of extraction, i.e. the point in time at which the residual is extracted from the industrial process, has a crucial influence on whether and within which valorisation pathways a residual may be valorised. This is especially an issue during industrial processes where the produced residual biomass streams have to be declared waste upon leaving the process (if not immediately treated as a food resource) and therefore are unavailable for further valorisation.

In addition, most processes, especially those requiring extreme temperatures or pH levels, affect the availability of valuable compounds or compound fractions within residuals. For example, protein fractions in residuals denature when exposed to high temperatures or acidic/basic pH levels. In order to valorise residuals from industrial processing, it is therefore essential to identify how certain process steps affect the quality of the residuals produced and to determine the ideal extraction times to secure the residuals before they are negatively affected or declared as waste, without compromising the integrity of the production process or the quality of the main product produced.

12.2.3.2 Processing and Extraction Technologies

For the downstream and industrial processing of biomass, there are a variety of processing routes that make use of different processing methods and process technologies to convert the biomass into a product. The decision for a certain processing pathway, its processing routes, processes and technologies has a deci-

sive influence on the residuals´ composition and hence their ability to be valorised within different valorisation pathways.

At the most basic level, the decision for a certain processing pathway, route or process results in the production of different residual streams, as all processing technologies determine the concentration and quality of other non-target compound fractions in the residual stream. For instance, during oil production, the quality of the protein fraction contained in the source biomass may be diminished due to excessive heat resulting from the pressing process, resulting in a low-value protein residual. Similarly, highly acidic or basic pH levels, rapid temperature changes or mechanical stress during processing, as well as microbial degradation or metabolic processes, may have a similar effect. Once a residual is established, the main influencing factors that affect the concentration and quality of the chemical components in the residual biomass are storage, transporting and packaging measures.

At a more sophisticated level, such effects may also be observed within different process lines of the same processing process, as well as within individual batches of a single process line, due to a lack of industrial standardisation and process-internal variability. Thus, several different residuals are produced within the same or similar processes, making their valorisation a challenge. A possible solution to this issue may be to define quality parameters in analogy to the target parameters of the target product and to develop a standardisation procedure that produces a consistent quality residual stream (e.g. by creating a blend of different biomass input streams that enable the production of the target product).

At the same time, the decision for a certain processing technology will influence the extractable amount of compounds in the residual biomass. This is because the extractable amount of a compound is typically significantly lower than the total compound amount contained in a residual biomass stream. For example, although a residual may possess a proven crude protein content that represents 30% of the total biomass, only a fraction can be extracted for use in bio-based applications or food production, with the exact extractable amount varying greatly depending on the extraction technology used. In many cases, the extractable amount of a compound found within literature is closely linked to the respective application scenario and the entailed technology, and therefore cannot be considered universally achievable.

Furthermore, while it is tempting to conclude that this relationship might allow for a general limit at which the extraction of a compound is worthwhile, this is unfortunately not possible, as even small concentrations of compounds may command high prices, as in the case of lupine oil, which fetches high prices on the essential oils market.

12.3 Understanding the Composition of Residual Biomass

The valorisation of residual biomass may be accomplished through one or a combination of several of the following three main modes of operation:

1. Valorisation of the residual as a whole based on its integrated use, which involves converting the entire residual biomass into a bio-based product (e.g. use of residuals as construction or packaging material).
2. Valorisation of the residual through its use as a substrate for a biological or chemical conversion process that produces a bio-based product or an intermediate (e.g. use of residuals as fermentation or fungal cultivation substrate).
3. Valorisation of the residual based on the extraction of single compounds or compound fractions that are of interest to a specific industrial sector because they represent a component of a target product, a platform chemical/material, or an essential substrate for the production of a target product (e.g. use of residual biomass for the extraction of dietary fibres or proteins to produce food products).

Of all of these modes of operation, the latter option represents the currently most prominently used and highlights that knowledge regarding a residual's composition is essential

Excursus 12.2: The Sustainability by Design Concept

Sustainability by design is a concept that aims to guide the valorisation of residual biomass and the creation of new valorisation pathways towards environmental, economic and social sustainability. The concept therefore assumes that in the future, residuals will no longer be seen as waste, but as a valuable source of biomass for bioeconomic processing solutions. Future sustainable and resilient agri-food systems will hence include all parts of the plant as equally interesting production outputs of commercial interest. In this way, 'former' residues will become tradable commodities and can be established as a local resource for bio-based products, in line with the food-first principle.

Furthermore, the future valorisation of residuals will be integrated into the strategic planning and operational management of farmers and processors. At farm level, the production focus therefore must shift from focusing solely on the quality parameters of the main crop to ensuring that by-products are part of the management focus and that their harvesting is ensured with the right timing and technology. In addition, approaches to stabilise and standardise crop residues immediately after harvest are needed to enable the purchase of by-products for food production. At a structural level, future networks of processors will work together, cascading the first and consecutive residual streams to ensure that biomass is used several times before the final residual is used to produce valuable bio-based fertiliser or compost. Cascading processing will thereby incorporate new and emerging green extraction and processing technologies.

The concept of sustainability by design therefore focuses on valuing the biomass once produced in such a way that it is optimally utilised through bioeconomic processing solutions, taking into account the food-first principle (see ► Chap. 1). As such coordinated cascading value chains currently do not exist, the implementation of the concept will require further prototyping and evaluation for proof of concept.

to determine the available valorisation pathways and hence the valorisation potential (Tuck et al. 2012; Gregg et al. 2020; Voogt et al. 2023; Joshi et al. 2024).

In general, the suitability of a residual for any given valorisation pathway depends on the overall and specific composition of the residual in terms of components relevant to producing value-added products. The bioeconomic value and potential of a specific compound fraction, in contrast, depend on the size of the fraction as well as how easily it can be separated from the remaining residual biomass. At present, there is, however, no specific bioeconomic value declaration that specifies the bioeconomic value of a residual, considering the various valorisation pathways available for different compound fractions.

As a result, current value assessments and general compound systematics borrow heavily from existing classifications within the food, material and bio-chemical sciences. For instance, compound fractions are typically assigned a nutritional or energetic value and are classified within existing systems (e.g. as macro- and micronutrients).

In the following, compounds will be classified into main and minor fractions, based on the proportion of the compound fraction within the overall composition of the residual as well as the ease of separating it. As such, the main fractions typically represent the largest proportions of compounds within the residual that can be easily extracted, whereas the minor fractions are found in smaller volumes or require more sophisticated extraction methods.

12.3.1 Main Fractions

The main compound fractions within residual biomass include fibres, proteins and amino acids, fats and oils, as well as non-fibre carbo-

hydrates such as starches and sugars. For first-stage residuals, their volume typically corresponds to the original volume found in the crop of origin, while for consecutive stages their volume depends on the influence of prior processing. The quality of the main fractions is strongly influenced by the technologies of the prior processing, which determine what part of the main fraction may be fractionated and used for further valorisation.

The following section provides a more detailed insight into the characteristics of the main fractions and their value in the context of a sustainable and circular bioeconomy. The fractions are presented according to the hierarchy in which they occur in the total available biomass, mainly derived from plants, trees or microorganisms on Earth.

12.3.1.1 Fibres

The term fibres represents an umbrella term that summarises various polysaccharides, including cellulose, hemicelluloses, lignin and pectins. All plants, but especially those of a certain height, contain these polysaccharides, as they serve as the main structural element that provides shape and rigidity to different plant tissues. As such, fibres are found in stems, branches and roots, as well as in flowers and fruits, and are the reason why plants can grow to a certain height (Thomas et al. 2003). Although flowers and fruits also contain fibres, they do not contain as much as the vegetative parts (i.e. roots, stems, leaves) of a plant.

Much of the residual biomass from agricultural production and forestry consists of leaves, stems or other woody material such as cuttings and therefore high levels of fibre. Similarly, processing residuals commonly comprise husks, shells or peels, as the food industry, mainly uses the fruit without its shell, husk or peel.

At the same time, processing activities (including harvesting) affect the qualities of fibre fractions contained within a plant, so that fibres from residual biomass are typically shorter and of lower quality than those obtained directly from wood or purpose-grown fibre plants such as hemp or flax.

From a chemical point of view, fibres are long-chain carbohydrates that consist of several, linked monomeric sugar molecules. The bioeconomic valorisation of fibres extracted from residual biomass may hence not only involve the use of the fibre in its entirety but may also entail splitting the fibre into its individual molecules using hydrolytic or enzymatic processes.

► Example: Valorisation of Fibres

Fibers from various residual streams may be valorised as functional fibres. Companies such as J. Rettenmaier & Söhne GmbH & Co. KG offer several different types of functional fibres that translate their natural function into products for our everyday lives. These include dietary fibres as well as fibres for fluid management, pharmaceutical applications (e.g. excipients) or as thickeners in food applications. The residuals from which these functional fibre products are derived are residuals such as apple pomace, citrus peel, rice hulls, or de-starched potatoes. ◄

12.3.1.2 Proteins

All plants contain a variety of different proteins which serve a wide range of cellular functions, including photosynthesis, biosynthesis, immunity, transport and storage (Rasheed et al. 2020). The chemical building blocks of proteins are amino acids, which are linked by strong covalent peptide bonds and have multiple levels of structure based on molecule internal interactions.

Proteins are found across all plant tissues and are hence abundant in both the main crop and many of the plant parts considered residual biomass. They typically occur together with oils and lipids, so that protein-rich residuals are common by-products of oil extraction.

The bioeconomic valorisation of proteins extends from the use of protein-rich meals, protein concentrates (60–85% protein content) and protein isolates (>85% protein content) to the use of individual amino acids across several sectors. In the food sector, in particular, protein has regained popularity as an extraction component for use in plant-

based food products. Proteins are therefore extracted from pulses, beans, but also from brewer's spent grains or okara from plant-based milk production.

► Example: Valorisation of Proteins

Proteins extracted from residuals, such as press cakes from oil production, have unique foaming, gelling, film-forming and water-binding properties that offer great potential for a wide range of technical applications. These proteins can be used as additives in paints, adhesives, lubricants, building materials, detergents or polymers. Residual-derived proteins thus enable the development of novel, sustainable, bio-based products with properties that in some cases even surpass those of fossil-based products of the same category (Fraunhofer-Gesellschaft 2021). At the same time, proteins derived from residual streams can also be upcycled to produce new plant-based foods, as shown in the example of brewer's spent grains in ► Sect. 22.4.3. ◄

12.3.1.3 Lipids

The term 'lipids' incorporates different forms of derivatives of long-chain monocarboxylic acids (so-called fatty acids). These include simple derivatives, such as fats and oils (triglycerides), waxes and esters, in which the fatty acids are bound to glycerine or glycerol, respectively, but also more complex molecules, such as phospholipids and glycolipids that contain additional building blocks.

Like proteins, lipids are contained in almost every cell of an organism, where they serve a variety of purposes. Plant-based fats and oils are typically found in kernels or seeds, as well as in some instances of fruit pulp, all of which are produced as a result of the production of the main product. Examples of oil-rich by-products from processing include raspberry seeds from jam production or oil-rich apricot and cherry pits.

The bioeconomic valorisation of lipids, at present, mainly focusses on the use of fats, oils and waxes and their individual fatty acid building blocks. Typical residual-based products derived from those fractions include food-grade oils, industrial oils as well as lubricants and detergents.

► Example: Valorisation of Oils

Oils derived from various residual streams typically have a high potential for valorisation, especially in the food and cosmetics industries. The Austrian start-up company 'Kern Tec' has developed a process for extracting the oils from the seeds of plums, apricots and cherries, which are left over from the production of juice or jam. The oils obtained by pressing the seeds are rich in unsaturated fatty acids such as oleic and linoleic acid and are used to produce vegan milk and cheese alternatives, breakfast spreads and culinary oils, while also being sold as the base for cosmetic products (Kern Tec GmbH 2024). ◄

12.3.1.4 Non-fibre Carbohydrates

Carbohydrates, along with fats and proteins, are among the most important building blocks of living organisms. They are organic compounds contained in every animal and plant cell and are typically composed of several monomeric units (e.g. glucose) that are formed as a result of photosynthesis (see ► Sect. 5.2). Aside from fibres, carbohydrates comprise several types of monomeric, dimeric and polymeric sugars (including glucose, fructose, mannose, lactose and sucrose) as well as complex starches (i.e. amylopectin and amylose). They all serve primarily as energy carriers but are also involved in intracellular and extracellular signalling pathways.

While the extraction of sugars from biomass is well established for traditional crops, such as the extraction of sucrose from beet roots or sugar cane, bioeconomic valorisation routes for the extraction of sugars are still heavily researched. For instance, residuals with high sugar content may be used as feedstocks for fermentation-based valorisation or synthesis pathways (see ► Sect. 24.2). In addition, biorefinery processes can also extract and convert sugar compounds from lignocellulosic residuals such as rice hulls from rice milling, coffee chaff from coffee roasting or sugarcane bagasse from sugar production.

► Example: Valorisation of Sugars

Sugar beet molasses is a residual of the well-establish sugar refining process and contains up to 50% sugar, making it an interesting resource for various sectors. While sugar beet molasses has traditionally been used as a feed additive, it may also serve as a carbohydrate source for fermentation processes. As such molasses may be the substrate for various bacteria and yeast species, allowing the production of bioethanol as well as various microbially derived lipids (e.g. cellobiose lipids, mannosylerythritol lipids, or polyol lipids), which have proven to be promising detergents, emulsifiers and active ingredients in cosmetics, crop protection and industrial and pharmaceutical applications or may serve as sustainable alternatives to palm oils (Boldt 2022; Beck and Zibek 2024; Südzucker2024). ◄

Starches, on the other hand, are a versatile biomaterial with properties of interest to a wide range of industries. As such, starch-rich residuals may be used for the production of dairy products, bakery products, soups, sauces, food coatings and meat products. However, they may also be used in pharmaceuticals, textiles, alcohol-based fuels, adhesives, paints and furniture (Kaur and Sharma 2019).

► Example: Valorisation of Starch

Starches derived from various residual streams such as potato peels are currently mainly used to produce biopolymers such as thermoplastic starch, polylactic acid, polyhydroxybutyrate or other starch-based polymer blends. The conversion is typically achieved by hydrolytically or microbially de-structuring the starch molecules to obtain glucose that may be metabolised by various microorganisms that produce the basic units (e.g. lactic acid) from which polymers may be formed (Ifbb - Institute for Bioplastics and Biocomposites 2018; Thielen 2020). ◄

12.3.2 Minor Fractions

Aside from the main compound fractions, residual biomass typically contains several different types of minor compound fractions, which are often grouped together as secondary plant compounds. These compounds serve a wide range of different functions within the plant, and their availability within first-stage residuals is heavily dependent on the variety of the plant, its growth stage, as well as the plant tissue in question (Wojdyło et al. 2022). In the case of consecutive-stage residuals, their quality and quantity depend significantly on the influence of prior processing, to the extent that certain processing operations may make their extraction impossible. An overview of the various minor compounds contained in residual biomass streams is provided in ◘ Fig. 12.4.

One of the most widely studied phytochemical fractions are polyphenolic compounds (also referred to as 'phenolics' or 'polyphenols'). Polyphenols are a diverse group of compounds found across various plant species where they serve a wide range of functions, including the prevention of oxidative stress, the provision of antibacterial and antifungal properties, or pigmentation.

For the bioeconomy, polyphenolic compounds from residual biomass streams (e.g. grape seeds and skins, olive oil press cakes or citrus fruit peels) are discussed and researched for a variety of applications, including flavouring and colouring agents in food products (e.g. orange peel polyphenols). Polyphenols have been used as food additives to impart bitterness to foods and beverages, antioxidant and health-promoting molecules in pharmaceutical, nutraceutical and cosmetic products, as well as novel functional molecules in biomaterial preparations, hydrogels and nanocomposites to name but a few (Panzella et al. 2020; Manso et al. 2021).

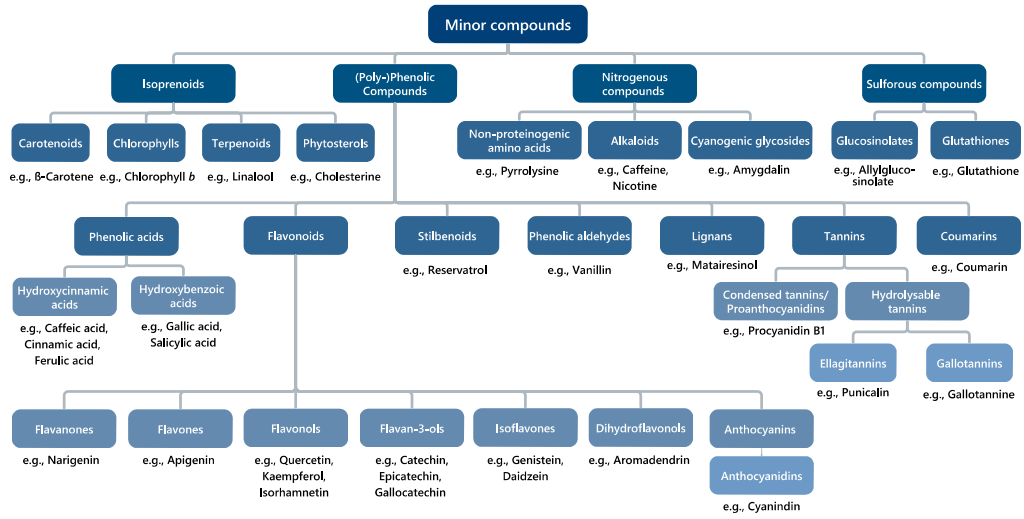


Fig. 12.4 Overview of minor compounds contained within residual biomass streams

Questions

1. Why is it difficult to come up with a general and specific definition of residuals?
2. What is the difference between first-stage, consecutive-stage and final-stage residuals?
3. Why are irregularly occurring residual streams, as opposed to regularly expectable residual streams, difficult to valorise into value-added products?
4. What is the importance of knowing the origin of a residual biomass stream when establishing a new supply chain?
5. What are the main fractions of residual biomass streams? For each fraction, give an example of a possible residual containing that fraction and a production that can be obtained from valorisation of the main fractions.

Answers

1. The term ‘residual’ represents a dynamic term, as the nature of a residual is determined by the current use of the main product. As the main (primary) product and its processing pathways are not constant but change over time due to changes in the technology landscape as well as the social and political context, residual streams and their definition are in a constant flux.
2. In contrast to first-stage residuals, whose quality and valorisation potential depend mainly on the impact of factors influencing crop management, consecutive-stage residuals have been affected by the processes applied to valorise the first-stage residual. As a result, they are typically of lower quality and may no longer be suitable for bioeconomic processing solutions of equally high value. Final-stage residuals can no longer be valorised to produce a value-added product but must be converted by composting or anaerobic digestion and returned to the field or disposed of.
3. Unexpected residual streams typically occur in large quantities. If processing facilities are available on site, they are usually already operating at capacity,

making it financially viable to maintain them. Such unexpected quantities are therefore problematic and can often only be processed manually or must be preserved in some other way until they can be processed again.

4. The concept of a sustainable and circular bioeconomy emphasises the importance of the local sourcing of raw materiials to create more resilient supply chains. It is therefore essential to understand where residual streams may occur, to gain insight into the processes from which they may originate and their potential producers. Gathering this information is the first step in establishing a value-web and helps to identify and connect all the relevant actors needed to transform the biomass stream into a commercially relevant stream that can be used to create a value chain for bio-based products.
5. The main fractions of residual biomass streams are:
   - Fibres
     - Residuals: Leaves, stems, wood cuttings, residuals from grain processing such as husks and shells.
     - Exemplary products: food additives, pharmaceutical auxiliaries, composite materials, textiles
   - Protein
     - Residuals: Seeds and kernels, leaves, oil production press cakes
     - Exemplary products: Meat alternatives, paints, adhesives, lubricants, building materials, detergents or polymers
   - Non-fibre carbohydrates
     - Residuals: Sugar beet molasses, Sugar cane bagasse, Potato peels
     - Exemplary products: Fermentation substrates for the production of bioethanol and microbially derived lipids (e.g. cellobiose lipids, mannosylerythritol lipids, or polyol lipids) or biopolymers
   - Lipids
     - Residuals: Seeds and kernels, fruit pulp
     - Exemplary products: Food-grade oils, industrial oils, lubricants, laundry detergents.

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Biogenous Waste Management

Stefan Salhofer and Erwin Binner



Fig. 13.0 About ▶ Chap. 13—biogenous waste management. (© Erwin Binner) (▶ https://doi.org/10.1007/000-htr)

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Biogenous waste (also biogenic or bio-waste) makes up a large proportion of municipal waste. This chapter begins with a definition of biogenous waste and a description of the quantities generated. It then addresses food waste as a major part of biogenous waste. A prerequisite for the treatment of this waste is its separate collection, which has been widely introduced in the EU member states. The processes and techniques used for composting and digestion, as the most relevant treatments for biogenous waste, are explained. The resulting compost and digestate are used as fertilisers and soil improvers, but their application may be limited by their heavy metal or nitrogen content.

Learning Objectives

After studying this chapter, you will…

- …be able to explain why biogenous waste treatment is important for closing natural material cycles (see ► Sects. 13.1 and 13.2).
- …be able to name and explain the differences between aerobic and anaerobic degradation processes (see ► Sect. 13.3).

13

13.1 Waste Types Containing Biogenous Fractions

According to the European Waste Framework Directive's definition, bio-waste comprises 'biodegradable garden and park waste, food and kitchen waste from households, offices, restaurants, wholesale, canteens, caterers and retail premises and comparable waste from food-processing plants'. Food waste, a major component of bio-waste, can be edible (e.g. food purchased but not eaten, leftovers from meals) or non-edible (e.g. banana peel, bones). The edible part is targeted by food waste prevention measures.

Amounts, Potential and Characteristics

The amount and composition of bio-waste from households and similar establishments vary greatly depending on the season, annual precipitation, settlement structure and other factors. When comparing collection rates, it is important to bear in mind that home composting and community composting are usually not included.

In 2022, around 60 million tonnes of bio-waste were collected separately in the EU27, of which 38 million tonnes came from households and 21 million tonnes from non-household sources (hotels, restaurants and catering; landscaping, parks and gardens; commercial and industrial sources and others). The largest part (88 %) of waste used for composting is collected from households and parks, while waste used for anaerobic digestion (AD), 46 % originates from households and 43 % from commerce and industry (ECN 2022).

A large proportion (around 60 %) of bio-waste from households and similar sources (= waste collected together with household waste, e.g. commercial waste) is *food waste*. More than with other types of waste, the prevention of food waste is perceived as an ethical responsibility for society. It is associated with a waste of economic resources and the resulting negative environmental externalities. The most common approaches to reduce food waste are information campaigns to raise awareness. Other common measures are food redistribution platforms and the promotion of the sale of second-class food by retailers. An analysis of the environmental impact of food waste (Scherhaufer et al. 2018) concluded that the food production phase accounts for almost three-quarters of the greenhouse gas emissions associated with food waste, and that the effects of food waste treatment and disposal are not the main cause of food waste-related impacts. ◘ Table 13.1 shows the quantities and value of wasted food for a number of case studies. Overall, the value of food waste for the EU in 2012 was estimated to be around EUR 143 billion.

Separate Collection of Biogenous Wastes

There is wide variation between countries and regions in terms of collection schemes and collection rates, which range from 28 to 328 kg/capita*year. According to BIPRO (2015), the most common primary collection scheme for bio-waste in EU member states is door-to-door collection, with additional col-

Table 13.1 Food waste, quantities and cost

Country, year of reference	Avoidable food waste (kg/cap*yr)	Cost of food waste (€/kg)	Cost of avoidable food waste (€/cap*yr)
Netherlands, 2013	47	3.2	150
Netherlands, 2019	34	3.5	119
Germany, 2012	53	4.4	233
Norway, 2015	42	6.1	256
Finland, 2011	23	4.0	92
Belgium, 2016	37	4.3	159

Source: Brusselaers and van der Linden (2020)

lection at civic waste recycling centres offered in all countries. For composting, the collection rate is 29–151 kg/capita*year, with a median of 72 kg/capita*year, for anaerobic digestion (AD), the median collection rate is 48 kg/capita*year (ECN 2022).

In most countries, higher quantities are collected for composting than for anaerobic digestion (e.g. Austria 146 kg/capita*year for composting and 80 kg/capita*year for AD). However, some countries rely more on AD and collect higher quantities for this treatment path, e.g. Flanders, where 232 kg/capita*year are collected for AD and 151 for composting (ECN 2022).

Introducing and maintaining a separate collection of bio-waste requires knowledge and commitment on the part of citizens. Intensive public relations work is required first to persuade people to collect their bio-waste separately, and to avoid contamination and the introduction of unwanted materials. A specific challenge in recent years has been the fact that non-degradable plastic bags often end up in bio-waste collection bins because they are mistaken for biodegradable bags.

Markets for Compost

In order to close the bio-waste loop, the compost and digestate produced from bio-waste should be of high quality so that they can be used as soil improvers or fertilisers. To create a market for compost and digestate, quality control of the process and the end products is very important as an integral part of a bio-waste management system. The aim is to build confidence in the end products by guaranteeing their quality.

Biogenous Fractions in Residual Waste

In Austria, *residual waste* refers to waste from households and similar sources that is not collected separately but is collected via the municipal waste collection system. Other terms for residual waste are *mixed municipal waste* and *household waste*. Residual waste excludes all materials that are collected separately, such as recyclable waste materials and biogenous wastes, bulky waste, electrical and electronical waste, used batteries, hazardous waste and street sweepings.

The composition of residual waste (the amount generated in Austria in 2020 was approx. 2,102,538 tonnes) is determined, for example, by the waste collection system, the socio-economic stratification of the population and the settlement structure. Despite the very well-established separate collection of used and recyclable materials in Austria, residual waste contains a significant proportion of biogenous materials. In an analysis of residual waste carried out in 2018/19 (Beigl 2020), the proportion of biogenous waste averaged 33.4 %. Residual waste therefore represents a potential for biogenous waste that should not be underestimated (extrapolated to the whole of Austria, it amounts to approx. 700,000 t of biogenous materials).

13.2 Possibilities for the Utilisation of Biogenous Wastes

Bio-waste can be used to produce organic fertiliser and/or energy by composting and/or anaerobic digestion. It can also be utilised as feed for insects, however, there are legal

restrictions on the use of the insects as food or feed. Other options, as described in ▶ Chaps. 17, 18 and 19 include biorefineries, biotechnological and thermochemical conversion, and the extraction of natural compounds.

Biogenous waste can be utilised *aerobically* (composting) or *anaerobically* (digestion in a biogas plant). The suitability of a waste for either process depends on its composition. Wet, low-structure waste with a high content of easily microbiologically available components (e.g. food waste, kitchen and canteen waste, grass cuttings, market waste, surplus food, slaughterhouse waste, brewery residues, fats, oils and also sludge) is better suited for anaerobic digestion. Dry, wood-rich waste (tree and shrub cuttings, household biogenous waste, digested sewage sludge, dry agricultural residues) is more suitable for composting (wood is not anaerobically degradable).

Treatment plants that co-process waste are subject to waste legislation and require authorisation from the relevant authority to treat the waste. The digestate only loses its status as waste once it has been properly recycled. If, on the other hand, only farm manure, renewable raw materials or energy crops, or crop residues are used in biogas plants, the digestate is referred to as biogas slurry and never enters the waste management system. However, its utilisation in agriculture is subject to legal regulations such as the EU Nitrates Directive (EEC 91/676 1991) and national regulations such as the Austrian Water Act (BGBl. 215/1959 1959).

13

13.2.1 Composting

Fundamentals of Composting

Since 2001, Austria has been in the fortunate position of having a compost ordinance (BGBl. No. II 292/2001 2001). This is the only regulation in Europe that defines an end-of-waste (EoW) status for compost. Compost (produced in accordance with this ordinance) is a freely marketable product. In other EU countries, the EoW status is only achieved through approval as a fertiliser.

> ***Composting*** is defined as the "controlled, aerobic, exothermic biological transformation of biodegradable biogenous materials (including a thermophilic phase) into a product rich in stable humic compounds with an organic matter content of at least 20 % DM" (Austrian Compost Ordinance 2001).

The rotting (composting) process takes place under controlled conditions. Therefore, it must be possible to intervene at any time if necessary to optimise the environmental conditions for aerobic microorganisms. A sufficient oxygen supply must be ensured through technical measures (e.g. pre-treatment of the input materials to generate a sufficient volume of air-filled pores, regular turning, forced aeration) so that the process can proceed *aerobically*. Furthermore, a sufficient *moisture* content must be ensured through the appropriate addition of water, both to the input material and during the rotting process. Microorganisms can only absorb oxygen and nutrients in dissolved form. A favourable *nutrient distribution* (the C/N ratio = carbon/nitrogen ratio is important) must be established during the preparation of the input material. This is achieved by the appropriate mixing of the available waste fractions.

Exothermic means that energy is released by microorganisms in the form of heat during the rotting process. This is only possible under aerobic environmental conditions and is important for three reasons. Firstly, this generation of heat enables the process to pass through different temperature ranges, allowing different types of aerobic microorganisms to participate and thus more 'complete' degradation and conversion of the various organic substances contained in the bio-waste. Secondly, the heat generation leads to temperature stratification in the windrow (the compost heap). This promotes natural aeration of the rotting material by convection. Thirdly, the heat generated leads to a temperature increase into the thermophilic range (>55 °C). This high-temperature phase guar-

antees the *hygienisation* of the rotting material, and the compost produced is free from pathogens and seeds.

The end product of the process (the compost produced) should have the highest possible content of stable organic matter (humic substances). For this reason, a minimum organic matter content of 20 % DM (determined by loss on ignition) is required. This means that the aim of composting is not to mineralise the original organic matter, but to convert it into stable humic compounds.

The presence of molecular fragments is essential for the formation of humic substances. The 'building blocks' from which humic substances are constructed come from various compounds (lignin, colouring and tanning agents, aliphatic structures, etc.). Too rapid mineralisation reduces the formation of humic substances because the fragments required for humic substance synthesis are mineralised immediately. However, insufficient decomposition of the rotting material is also detrimental. A diverse composition of the input mixture is essential for intensive humic substance formation. It requires both readily and moderately to poorly available organic components, so the rotting mixture should consist of as many different biogenous waste fractions as possible. One-sided material composition (composting of green waste only, composting of sewage sludge only) tends to result in less humic substance formation.

Composting Techniques

In technical composting, a distinction is made between open and closed composting systems. Traditional windrow composting systems are referred to as open systems. In this system, the windrow surface is in direct contact with the outside air. Water vapour and gaseous metabolic products, dust and fungal spores are released into the environment. In open systems, the microorganisms are usually supplied with oxygen naturally (by convection) or (much more rarely) by forced aeration (suction or pressurised ventilation).

Convective aeration requires careful pretreatment of the input mixture (sufficient proportion of structural material) as well as appropriate dimensioning and management of the windrows. The intensive rotting period is 7–10 weeks. Depending on the intended use of the compost produced, a further 4 to 20 weeks of maturation is required. Triangular windrows with a maximum height of 2.2 meters are suitable for natural aeration; the height can be increased to up to 2.5 meters if the proportion of structural material is very high.

Figure 13.1 shows a naturally (convectively) aerated triangular windrow. The energy released during aerobic decomposition heats the rotting material and the pore air respectively (self-heating). If there is a sufficient proportion of air-filled pores (free airspace = FAS), the warm exhaust air (low O_2, high CO_2) flows out through the surface layers. The resulting negative pressure in the core of the windrow allows fresh, oxygen-rich air to flow in laterally at the base of the windrow. If the base of the windrow becomes compacted or waterlogged due to excessive weight or lack of structural stability of the material, the fresh air required can no longer flow in, as there are not enough air filled pores or they are filled with water. At the same time, the exhaust air can no longer flow out, resulting in insufficient gas exchange via the windrow surface (only by diffusion). The heat released remains in the windrow and stimulates intensive rotting processes.

The loose structure of the material must therefore be maintained by regular turning with a suitable windrow turner (wheel loaders are no longer considered suitable). The minimum turning interval during the intensive rotting phase is 7 days. The air introduced during turning only contributes to the oxygen supply for a short period of time; the oxygen introduced is consumed by microbes within 15 to 30 minutes. Triangular windrows higher than 2.2 meters and table windrows must be forced aerated (pressurised or sucked). Forced aeration does not influence the turning interval.

Closed systems (reactor systems) have been developed to better control or intensify the biochemical degradation process. Compared to the open windrow rotting systems, the process is easier to optimise. The intensive rotting phase can be completed within 10 to 20 days. However, every closed system must be followed by a maturation phase - usually in an open windrow rotting

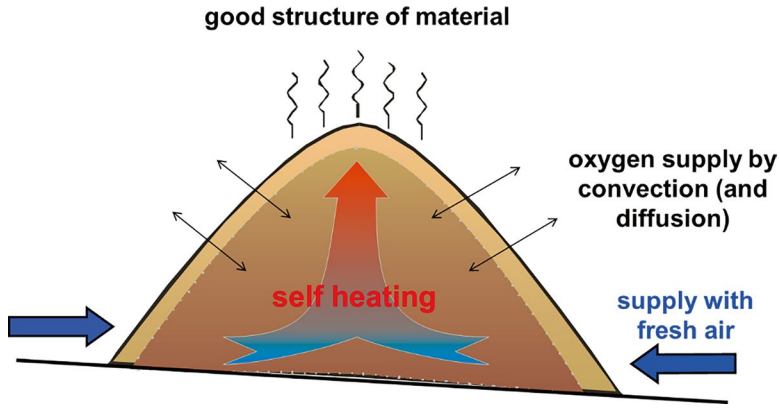


Fig. 13.1 Convective air flow (oxygen supply) in open windrow composting (Adopted from Binner (2024))

system. A major advantage of closed systems is that the exhaust air responsible for unpleasant odors can be captured and desodorised. The disadvantages are the higher risk of the rotting material drying out (dry stabilisation stops biological processes) due to the high air throughput and the increased tendency to mineralise the organic matter. The latter leads to significantly lower content of humic substances in the compost due to the extensive conversion of the organic matter into CO_2 and H_2O. Careful material preparation and regular turning are essential for proper operation, even in closed systems. Otherwise, drying out in areas with preferential air flow will slow the rotting process or lead to a lack of oxygen in the areas with less air flow, resulting in anaerobic conditions.

13

13.2.2 Anaerobic Digestion

Fundamentals of Anaerobic Digestion

While the excess energy generated during the aerobic decomposition of organic matter is released as heat, in the anaerobic process, this energy is stored in the biogas produced. Biogas is a mixture of carbon dioxide (CO_2, approx. 35 to 55 Vol. %) and methane (CH_4, approx. 65 to 45 Vol. %). In addition to the biomethane that can be utilised as an energy source, the anaerobic process produces fermentation residues (digestate) that contain the nutrients from the biogenous waste as well as organic substances that have not been converted into gas. Waste digestion is only considered recycling if the digestate is utilised, for example, as a soil improver or fertiliser in agriculture. Depending on the treatment technology used, this digestate is generated in solid and/or liquid form.

The digestion process can be divided into four sub-processes, which take place one after the other and to a certain extent side by side. In the first phase of *hydrolysis*, the high-molecular-weight organic compounds of the original substances introduced are broken down into simple organic compounds. In the *acidification phase* (acidogenesis), the water-soluble hydrolysis products are broken down into low-molecular-weight organic acids (carboxylic acids), alcohol, CO_2 and hydrogen. During *acetogenesis*, organic acids and alcohols are converted into acetic acid, CO_2 and hydrogen. Finally, in phase 4 (*methanogenesis*), strictly anaerobic microorganisms generate methane from acetic acid and hydrogen or from hydrogen and carbon dioxide. For process stability, it is important that acetogenic and methanogenic microorganisms 'co-operate' in terms of time and location. Acetogenic microorganisms use the energy released during the methanogenic process to form organic acids. However, if organic acids take over, the pH decreases and the methanogenic microorganisms stop their activity.

Anaerobic Technology

Anaerobic processes can be characterised as follows (Dieckmann et al. 2016):

- 'Single-stage' and 'multi-stage' processes are used. The purpose of multi-stage processes is to separate the four fermentation phases—this allows more defined environmental conditions to be set, which is particularly advantageous in the methanogenic phase.
- Depending on the water content of the substrate used, the process is referred to as 'wet fermentation' (water content > 85 % fresh matter) or 'dry fermentation' (water content < 80 to 85 % fresh matter). The advantage of wet fermentation is the pumpability of the substrate, which ensures homogeneous mixing. The disadvantage is that the final digestate must be dewatered, which can result in large quantities of wastewater.
- Depending on the fermentation temperature, a distinction is made between 'mesophilic' (35 to 42 °C) and 'thermophilic' (50 to 55 °C) processes. Thermophilic processes run more quickly (this means that the retention time spent in the reactor can be reduced). However, significantly more energy is required to maintain the temperature in the thermophilic range than in mesophilic operation (this reduces the net energy yield). An advantage of thermophilic processes is that substrate sanitisation (killing of pathogens, weed seeds and sprouting plant parts) can be ensured.
- Depending on the type of feeding, a distinction is made between 'continuous' operation and 'batch operation'. In continuous operation, substrate is fed in regularly (an equal amount of digestate is removed). In batch operation, the reactor is filled once and emptied completely after a defined retention period. The advantage of continuous operation is an improved operational reliability (the buffering effect of the already 'older' material prevents acidification of the substrate). The disadvantage is the more complex technology required to move the substrate.
- Based on the selected mixing or material transport through the reactor, a distinction is made between 'non-mixed', 'partially mixed' and 'fully mixed' systems. Batch systems are usually not mixed; in some cases, the percolate (leachate) is recirculated. In partially mixed systems (e.g. plug flow reactor), the substrate is slowly transported through the reactor by rotating paddles (horizontal reactor) or by gravity (vertical reactor). The advantage of both techniques is a defined residence time in the reactor. In fully mixed systems, the substrate is continuously stirred or pumped. The advantage is high homogeneity, the disadvantage is the risk of short-circuiting (theoretically, the newly added substrate can leave the reactor again immediately).

13.3 Utilisation of Compost and Digestate

Compost is an organic product enriched with humus and plant nutrients, used primarily to improve soil functions. Regular addition of compost maintains the permanent humus content of the soil and promotes microbial metabolism and soil organism activity.

In addition to a carefully conducted composting process, the quality of the input materials has a significant influence on the quality of the compost. Pollutants in the delivered waste contaminate the resulting compost. For example, heavy metals and microplastics are not degraded during the rotting process. In Austria, this was already taken into account in 1995, when a mandatory source separate collection of biogenous waste was introduced (BGBl. 68/1994 1994). In many other European countries, attempts have been made to achieve compost quality by processing mixed waste in the same way. Since 2015 (EU Circular Economy Package (COM 614 2015), Waste Framework Directive (EU-CD 2008/98/EC 2008)), composting has been recognised in the EU as a process for the material recovery (recycling) of waste if the waste used comes from a 'separate collection system'.

The legal regulations of the individual member states define minimum standards for compost quality and its monitoring (in Austria, by the Compost Ordinance, BGBl. II

292/2001 2001). Associations were founded in Germany in 1992 (Federal Compost Quality Association) and in Austria in 1994 (Compost and Biogas Association Austria/KBVÖ) with the aim of improving the quality of compost and promoting its marketing. Other countries followed and as early as 1999 the ECN (European Compost Network) was established as a network of quality assurance organisations for compost, producers of compost and fermentation products and related experts.

Table 13.2 shows the requirements of the Austrian Compost Ordinance (BGBl. II 292/2001 2001) as an example of heavy metal limit values depending on the application of the compost. Two quality classes for agricultural use (A^+ for organic farming and A for conventional agriculture) have been defined on the basis of heavy metal concentrations. Quality class B is intended for special applications (but not for agriculture). Limit values in other EU countries are in a similar range.

In addition to the heavy metal limit values, the application of compost in agriculture must comply with the EU Nitrate Directive (91/676/EEC) and, in Austria, the total nitrogen input according to the Water Rights Act (BGBl. 215/1959 1959), 1990 amendment. According to the Water Rights Act, a maximum of 175 kg total N/ha*a may be applied to areas without green cover and 210 kg total N/ha*a to areas with green cover. This regulation is viewed very critically, mainly because it does not take into account the form in which the nitrogen is bound. In compost, most of the nitrogen is bound in humic substances and in contrast to mineral fertilisers or digestates, it is not water-soluble and therefore not prone to leaching but readily available to plants (approx. 5–10 % per year). This leads to a scientifically unjustified restriction on the quantities of compost that can be applied.

In contrast to compost, there is no regulation in Austria on the end-of-waste status of digestate. Digestate from biogas plants resulting from the processing of waste is also classified as waste and only loses this status if it is properly utilised (recycled) in accordance with the legal framework. One way to leave the waste regime is to obtain authorisation from the relevant authority to use the digestate as fertiliser (EU Fertiliser Ordinance, EU 2019/1009 (2019), BGBl. 513/1994 1994 and BGBl. II Nr. 100/2004 (2004) respectively. Another difference to compost is the difference mentioned above in the form in which the nutrients and pollutants are bound. These are water-soluble in digestate and are therefore immediately available to plants as nutrients, but can also be washed out into the groundwater if not taken up by plants.

Table 13.2 Compost quality classes defined by Austrian Compost Ordinance (BGBl. II 292/2001 2001)

		Cd	Cr	Hg	Ni	Pb	Cu	Zn
		Quality A^+ (for organic farming)						
Limit value	mg/kg DM[a]	0.7	70	0.4	25	45	70	200
		Quality A (for conventional agriculture)						
Limit value	mg/kg DM	1	70	0.7	60	120	150	500
		Quality B (not for use in agriculture)						
Limit value	mg/kg DM	3	250	3	100	200	500	1800

[a]*DM* dry matter

Questions

1. Characterise the different types of biogenous waste and how they can be recycled.
2. Why is the supply of oxygen and humidity essential for the composting process?

Answers

1. Biogenous waste from households and parks is typically composted, while biogenous waste from commerce and industry, including some from households, is digested.
2. Microorganisms can only take up nutrients in dissolved form. Aerobic degradation does not take place without oxygen.

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Bio-Based Fertilizing Products: Closing Nutrient Loops by Recycling

Marielle Trenkner, Benedikt Müller, and Andrea Bauerle



Fig 14.0 About ▶ Chap. 14—fertilizing products. (© Universität Hohenheim, Max Kovalenko) (▶ https://doi.org/10.1007/000-hts)

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This chapter describes how recycling of plant nutrients from organic waste streams would reduce both resource waste and environmental degradation, while contributing to closing nutrient loops. By the examples of nitrogen (N) and phosphorus (P) fertilizers it is shown how bio-based fertilizing products (BFP) are obtained and applied in agricultural production.

Learning Objectives

After studying this chapter, you will…

- …be able to define bio-based fertilizing products (see ► Sect. 14.1).
- …be able to describe the origin, characteristics and application of bio-based fertilizing products (see ► Sects. 14.2 and 14.3).
- …be able to discuss the contribution of bio-based fertilizing products to a circular bioeconomy (see ► Sects. 14.1 and 14.3).

The main purposes of fertilizer application in agriculture include the supply of nutrients to crops to support the plant growth, and to maintain or improve the soil fertility.

A key approach to reduce resource dependency and to minimize environmental impacts in the bioeconomy is the recycling of nutrients. Crops require nutrients, predominantly nitrogen (N) and phosphorus (P) (see ► Sect. 6.9), which are considered two constitutional building blocks of life by the planetary boundary framework (see ► Sect. 1.3) (Richardson et al. 2023). These nutrients are traditionally provided by the application of conventional (=mineral or synthetic or artificial or mined) or organic fertilizers. However, conventional mineral N fertilizers are mainly produced using the Haber-Bosch synthesis, which is very energy-intensive and has a high climate impact due to the high proportion of fossil fuels used (Sigurnjak et al., 2017). Conventional mineral P fertilizers are produced by mining phosphate rock from global reserves, which are unevenly distributed and concentrated in specific regions (Nedelciu et al. 2019; Römer & Steingrobe 2018). Thus, the provision of synthetic fertilizer is not only energy and fossil-resource-use-intensive, but often their over-use results in nutrient runoff, contributing to soil and water pollution (Richardson et al. 2023; Steffen et al. 2015). Shifting to a more circular approach, nutrient recycling would reduce both resource waste and environmental degradation, while closing nutrient loops (Valve et al. 2020). A key approach to nutrient recycling involves transforming organic waste streams or by-products—such as animal manure, crop residues, food scraps and even human waste—into bio-based fertilizers or bio-based fertilizing products. For example, P recovery from wastewater and sewage sludge is a promising approach to capture nutrients from waste streams before they pollute water bodies.

14.1 Generation of Bio-Based Fertilizing Products

Bio-based fertilizing products (BFPs) can be defined as 'materials or products derived from biomaterials (plant, animal or microbial origin, often wastes, residues or side-streams from agriculture, industry or society) with a content of bioavailable plant nutrients suitable to serve as a fertilizer for crops', as suggested by Wester-Larsen et al. (2022).

BFPs can be generated through various methods, including anaerobic digestion (see ► Sect. 13.2.2), drying, incineration and operations in biorefineries (see ► Sect. 17.2).

> ***Bio-based fertilizing products (BFPs)*** are materials or products derived from biomass that contain a suitable amount of bioavailable plant nutrients to serve as a fertilizer for crops.

The utilization of sewage sludge from municipal wastewater treatment plants is a promising option for closing nutrient cycles. In these facilities, sewage sludge is converted into BFPs through technologies such as anaerobic digestion, thermal hydrolysis and combustion (Zahrim et al. 2019). These tech-

niques help reduce contaminants in the sludge, while maximizing nutrient availability to produce BFPs with high nutrient concentration (mainly P). Additionally, advanced techniques like struvite precipitation allow for the production of high-quality BFPs through the direct extraction of P. Sewage treatment plants therefore play an important role in closing nutrient cycles between urban and rural structures, thereby contributing to a more circular and sustainable bioeconomy.

Biomass resources (e.g. wood chips, straw) can be converted into biochemicals and biofuels in biorefineries (Ubando et al. 2021). This conversion often produces nutrient-rich (N, P, potassium (K)) by-products, which can be transformed into BFPs. Also, the extraction of nutrients from municipal wastewater bears a large potential for the production of BFPs and for closing the nutrient cycles between urban and rural areas. Manure and digestates derived after anaerobic digestion for the production of biogas for energetic applications (usually with other organic residues or specifically cultivated biomass crops), are common fertilizers in agriculture. Although they are BFPs in the narrower sense, as multi-nutrient fertilizers they can also be part of the over-fertilization problem. Over-fertilization occurs when the fertilizer dose is optimized with regard to a single nutrient and other accompanying nutrients are contained at a too high concentration and therefore in oversupply. Therefore, the term novel BFPs refers to fertilizing products that have a higher degree of processing, such as single nutrient or pelletized BFP derived from digestates or manure, in this case.

Novel BFPs were further defined in Wester-Larsen et al. (2022) as a BFP "produced by processes beyond simple biogas digestion of animal manures and simple composting." Simple composting proved not to be a suitable method for producing novel bio-based fertilizers, as nutrients and greenhouse gases are expected to be lost during the process, and the resulting products show no fertilizing effects without the addition of other fertilizers (Müller et al. 2024b). However, compost (see ▶ Sect. 13.2.1) can be considered a soil amendment and as such is also important for soil fertility in the bioeconomy. Processes involved in producing novel BFPs can, e.g. be mineral extraction, combustion, precipitation or drying and pelletizing/granulating. BFPs can be classified by their specific function (Product Function Category, PFC) and the raw materials used for their production (Component Material Category, CMC) in accordance with the EU Fertilizer Product Regulation (EC No 2019/1009). ◘ Figure 14.1 shows a pelletized BFP made from insect frass. This is an innovative BFP, produced as a by-product in insect-based biorefineries. This fertilizer typically contains N, P and K, in concentrations comparable to farmyard manure, as well as micronutrients (Houben et al. 2020). In addition to the nutrients, insect frass – and most BFPs on the market – are rich in organic matter, which enhances soil structure, water retention and microbial activity, contributing to long-term soil conditioning. ◘ Figure 14.2 shows pelletized fertilizer applied to the soil surface in a field with winter wheat production.

14.2 Fertilizing Effects

Phosphorus recovery from wastewater and sewage sludge has the potential to supply significant amounts of the phosphorus required in agricultural production. Phosphorus can be extracted from wastewater e.g. through struvite precipitation, producing a slow-release fertilizer, which accounts for long-term phosphorus stability in soil (Li et al. 2021; Wang et al. 2020). Studies have proven, that struvite recovered from waste streams can have a similar to even better phosphorus fertilizing effect on crops, when compared to mineral fertilizer (Ehmann et al. 2017; Müller et al. 2024a). Recovering phosphorus from various residues can therefore reduce the dependence on mined phosphorus and help minimizing the environmental impacts of phosphorus use, such as eutrophication.

Production of N-containing BFPs can reduce greenhouse gas emissions and the use of fossil resources because the production of conventional mineral N fertilizers is very energy-intensive (Sigurnjak et al. 2017). Of 18



Fig. 14.1 Pelletized BFP produced from insect frass. This example highlights how waste from insect production systems can be transformed into nutrient-rich fertilizers, supporting circularity in agriculture. (© Andrea Bauerle)

N-containing BFPs derived from agricultural, food industry or municipal side-streams tested at five field sites across Europe, the majority showed high mineral nitrogen fertilizer replacement values (Müller et al. 2024b). These BFPs included solid and liquid forms (Fig. 14.3). Another multi-year test of BFPs as substitutes for conventional mineral fertilizers showed that P-BFPs can be a reliable and sustainable nutrient source for crop rotations, whereas N-BFPs, as a main fertilizer for one crop, were found to be more prone to environmental influences (Müller et al. 2024a).

Figure 14.3 shows different N-containing BFPs in solid (pellets or granules) and liquid form, each derived from various nutrient-rich side-streams, reflecting the diversity of materials available for nutrient recycling. The very commonly used mineral N fertilizer, calcium ammonium nitrate (CAN), is on the left. The other bottles show the equivalent amount of BFPs that would be required to replace the N supplied as CAN. The required amount of BFP is higher, the lower the N concentration it contains.

BFPs, often rich in organic matter (see Fig. 14.4), are expected to enhance soil quality due to their positive impact on soil organic matter content (Wester-Larsen et al. 2024).



Fig. 14.2 Pelletized BFP applied in a winter wheat plot 12 (left) and 35 days (right) after application (© Andrea Bauerle)



Fig. 14.3 Bottles with calcium ammonium nitrate (CAN, left) and various BFPs (from left to right: feather meal; horn meal & pig bristles; liquid ammonium sulphate from biogas digestate; blood meal & feather meal; mixture of meat and bone meal, vinasse and chicken manure; fermented biochar with clay flour & rock flour; vegetable residues from wheat and maize), showing the BFP amounts needed to replace the nutrient value of CAN. (© Andrea Bauerle)

14.3 Application in Practice

Besides the described advantages, BFPs face several challenges when practically applied. These challenges include inconsistent concentrations or unfavourable composition of nutrients, potential contaminations and limited market acceptance (Smol 2021). Some BFPs have rather low nutrient concentrations. To make use of the nutrients still present in the BFPs, solid products could be mixed into a cultivation substrate for horticulture, or alternatively used as soil improvers, thus providing valuable organic matter and micronutrients to improve soil structure and fertility over time (Huang et al. 2021). Low-nutrient products could also be blended with fertilizer of higher N-P-K concentrations to replace at least a certain amount of mineral fertilizer, while still meeting the crops requirements. When producing liquid BFPs, a few more aspects have to be considered. Liquid BFPs pose challenges for storage and long-distance transportation, as transporting



Fig. 14.4 Dried solids from separated biogas digestates that is rather low in nutrients and high in organic matter and is applied as soil improver. (© Andrea Bauerle)

large volumes of water is typically not cost-effective. Instead, its use is best suited for local or regional application. According to Müller et al. (2024), when managing liquid fertilizers, effective integration into farming operations can be achieved through equipment such as star wheel applicators for injection (Fig. 14.5) or slurry tanks with dragging hoses or trailing shoes for ground-level application of the fertilizer. Additionally, liquid fertilizers can be well-suited for urban agricultural systems, such as hydroponics, where their use is already a standard practice (Haryanta et al. 2022). However, to successfully address these issues, further research is required in terms of purification technologies and regulatory frameworks to ensure safety and efficiency, increasing public acceptance.

Nutrient recycling for the production of BFPs aligns with the bioeconomy circularity principles through the transformation of waste streams into valuable resources. Following these principles, sustainable agriculture is actively promoted. Dependency on synthetic fertilizers is reduced, while environmental impacts from synthetic fertilizer production are mitigated. For the application and integration of BFPs into agricultural practice in a bioeconomy context, it should first be decided what the aim of the application is. If the primary objective is to supply nutrients, a BFP with a relatively high nutrient concentration (>10%) is advantageous to keep applied quantities within spreadable limits. If the objective is primarily to maintain or improve the soil health/quality/function, a BFP with low nutrient concentration, like composts



Fig. 14.5 Application of a recycled mineral fertilizer derived from digestates (liquid ammonium sulphate) with star wheel injection technology at the University of Hohenheim. (© Benedikt Müller)

(<5%) is recommended. The combination of both objectives can either be implemented by applying two or more different BFPs or by repeated application of a BFP with medium nutrient concentration. If the aim of the application is clear, suitable BFPs can be selected and are preferably integrated into the fertilization strategy of the respective farm.

Questions

1. What are bio-based fertilizing products (BFP) and when do we speak of novel BFPs?
2. What are the characteristics of BFPs that determine their use in agricultural production?
3. What are the potentials in recycling plant nutrients from waste streams?

Answers

1. BFPs are materials or products derived from biomaterials (plant, animal or microbial origin, wastes, residues or side-streams from agriculture, industry or municipalities) with a content of bioavailable plant nutrients suitable to serve as a fertilizer for crops. Novel BFPs are further processed using more advanced technologies (e.g. mineral extraction, combustion, precipitation or drying and pelletizing/granulating) into fertilizer that can be directly and effectively applied in agricultural production.
2. The main characteristic determining the use of BFPs in agriculture is the concentration and the ratio of plant nutrients. BFPs with a relatively high nutrient concentration (>10%) are applied as fertilizer when the primary objective is to supply nutrients. If the objective is primarily to maintain or improve the soil health/quality/function, a BFP with high carbon content and low nutrient concentration (<5%) is recommended (e.g. soil amelioration products).
3. Nutrient recycling for the production of BFPs aligns with the bioeconomy with circularity principles through the transformation of waste or side streams into valuable resources. All organic waste streams contain plant nutrients and recycling of plant nutrients can best be performed when biorefineries are directly installed at sites where the waste

streams are produced, such as biogas plants or municipal wastewater or sewage treatment plants.

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Digitalization in Agricultural Production

Anthony Stein



Fig. 15.0 About ▶ Chap. 15—digitalization in agricultural production. (© Universität Hohenheim, Wolfram Scheible) (▶ https://doi.org/10.1007/000-htt)

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This chapter touches upon the evolution and current trends of digital agriculture – especially the integration of artificial intelligence (AI) into agricultural technology. We start by discussing the general concept of digitalization and how it contributes to the transformation of farming practices. Afterwards, a short overview of past and current technological advances leveraging digital methods to improve agricultural practice, with a focus on crop or more generally biomass production, is provided. Then we cast light on how AI can be understood in this context and work out a generic perspective on intelligent agricultural technology. The latter concept is then used to first critically reflect on the current degree of AI utilization in agricultural technology and, in consequence, show potential pathways where and how AI and related advanced digital technology can foster bioeconomy.

Learning Objectives

After studying this chapter, you will...

- …be able to describe the field of digital agriculture and set it in context to its 'predecessors' precision agriculture and smart agriculture (see ► Sect. 15.2).
- …be able to define the term artificial intelligence (AI) in the context of agriculture (see ► Sect. 15.3).
- …be able to critically assess digital technologies and robotic solutions in crop production for their actual extent of embodying AI methods (see ► Sects. 15.2 and 15.3).
- …be able to discuss current obstacles and pathways to foster digitalization and AI in bioeconomy (see ► Sect. 15.4).

15.1 Digital Transformation

Our world gets more and more digital. This is due to a transformation process called digitalization. Digitalization impacts almost all sectors of our economy and even our daily lives. Just envision the possibilities you have at hand using your smartphone and the vast majority of apps. Artificial home assistants allowing to order groceries and commodities just by speaking to them. Smart home applications that allow remote or even fully automatized control over heating, shutters, even notifying you when to buy new food by monitoring the fridge. Not to forget little helpers close to the ground, vacuuming the floor or mowing your lawn. Looking to the industry side, digitalization has revolutionized the way products are manufactured, large warehouses are managed, or materials and products are delivered to retailers or consumers. Robotic applications and autonomous transport systems reduce manual labour and increase the degrees of process automation. Information systems such as enterprise resource planning and manufacturing execution systems are in place to monitor and optimize business and production processes along the different value chains. Likewise, the service sector was hit by the digitalization wave, what we can notice by receiving less paper-based invoices, insurance policies, etc., but are being referred to personal online customer portals, resulting in a multitude of inboxes.

Digitalization traditionally has been described as the conversion from once analogous information into digital counterparts for further processing through a computer. On the other hand, it has been more and more understood to also describe the handover of (repetitive) manual tasks to the computer, which allows for automatization of these tasks. Even closer to our today's understanding of the term, digitalization is often used synonymous with digital transformation or revolution. The latter terms originally refer rather to the change processes as facilitated by the technical digitalization and available digital technologies – comprising digital communication infrastructure, applications and also devices – which act as drivers of the transformation (BMLEH 2022; Hess 2019). Accordingly, today we often speak of digi-

talization when a company or institution adopts digital technologies to improve their production, manufacturing, or other business processes.

15.2 Digitalization in Agriculture

Naturally, digitalization has also started to pervade the agricultural sector for quite some time. It is a progressively appearing process that takes place on the scale of years and decades through novel innovations found by applied and transdisciplinary research and brought to the market through commercial start-ups or big companies promoting their newest technology to the agricultural consulting companies and farmers as end users. The result of the digital transformation of agriculture is commonly known under the name *digital agriculture*.

Digital agriculture serves as an umbrella term for a particular perspective on agricultural developments and innovations which are grounded in the utilization of both established and new digital technologies in agricultural processes, products and systems. It describes the solutions and new possibilities facilitated in the agricultural sector through the use of: (1) Sensors and Internet-of-Things (IoT) solutions to continually acquire data to be passed via (2) information and communication technology (e.g. wireless networks, cellular networks, Internet) to (3) adequate computing infrastructure (e.g. edge or cloud computing) or (4) smart devices (smartphones, tablets) running (5) application or analysis software to further process, enrich and thus add value to agricultural data and information. This added value then shall aid agricultural management, i.e. allow for improved decision-making, higher automatization of production processes as well as enhanced monitoring of any related activities and measures. Cf. also (Basso and Antle 2020; Paraforos and Griepentrog 2021; Papadopoulos et al. 2024). Digitalization of the agricultural sector further has the potential to benefit the entire agri-food value network through the provisioning of information derived from collected agricultural data.

Figure 15.1 illustrates the confluence of the two scientific disciplines agronomy and computer science, underlying digital agriculture, or else their resulting technologies, i.e. agricultural technology and (new) digital technologies. The latter technological advances are exemplarily depicted by precision agriculture (see definition below) on the left-hand side and artificial intelligence (AI) on the right-hand side. Figuratively speaking, the digital transformation of agriculture pushes the right bubble to the left so that the overlap between these disciplines increases which opens the space for new innovations in the digitized agricultural sector, such as intelligent agricultural technology (see definition below) and beyond, with strong potential for the entire bioeconomy.

15.2.1 Placement and Differentiation to Related Terms

Some authors argue that the terms *precision*, *smart* and *digital farming* are not defined precisely enough, as that would justify a concrete differentiation (Herlitzius et al. 2022, p. 121). Others attempt to integrate these terms highlighting the common objectives of all three concepts. According to a DLG position paper (DLG-Ausschuss für Digitalisierung, Arbeitswirtschaft und Prozesstechnik and Griepentrog 2019), the terms precision farming, smart farming and digital farming all share a common goal, namely the site-specific and most precise treatments of objects dealt with in agricultural production, but differ in the methods they use to achieve them. Besides the term *precision agriculture* is often used in the scientific

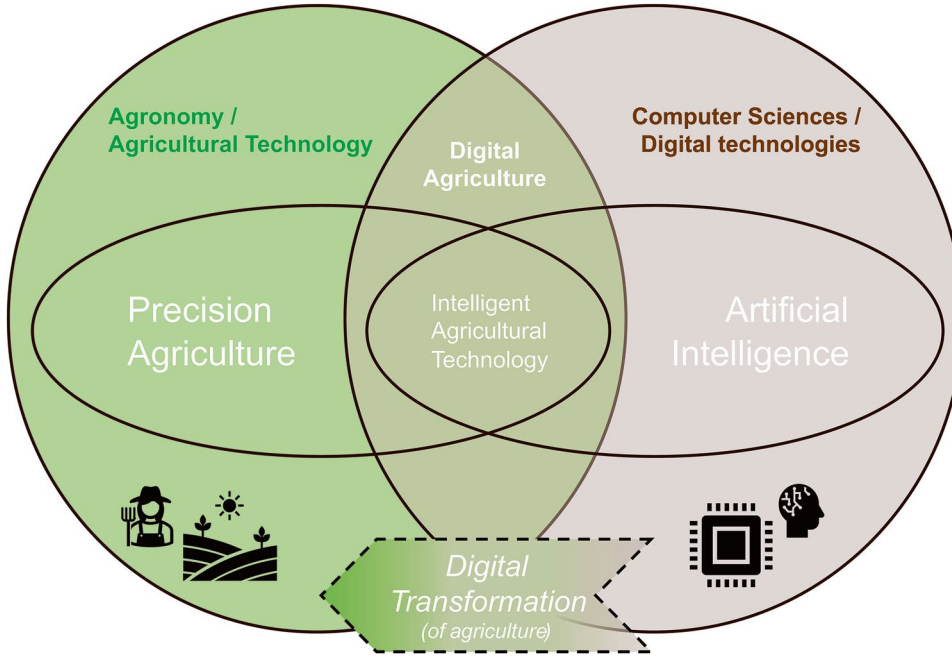


Fig. 15.1 Venn diagram illustrating the progressing confluence of the disciplines behind digital agriculture. (© Anthony Stein)

community[1]. Some use these terms interchangeably, some differentiate them. For the sake of simplicity, we denote these terms here by using precision agriculture as the broader term comprising both `precision (crop) farming' as well as `precision livestock farming' adopting the recently revised definition of the International Society of Precision Agriculture (ISPA). For the remainder of this section, however, we concentrate on precision (crop) farming and accordingly only will make use of this term.

The term *precision farming* was coined in the 1990s and describes the goal to apply the right input (fertilizers, plant protection products) in the right amount at the right time for the right spot in your fields and in the right manner (Kohsla 2010). Precision farming thus allows for what is called *site-specific management* of the fields to realize the aforementioned 'right' aspects. Against the background of spatial variability of soil conditions and nutrient availability for crops, being able to map the exact demands or potentials for high yields forms the basis for precision farming solutions. Technological advances implemented in modern mechanization, i.e. tractors and adaptable implements, paved way to at least partly achieve this goal. Among these technologies, most prominently automated steering systems, variable rate control as well as section control successfully entered the market.

Automated steering systems relieve the machine operators from manually steering the big and complex machines during field activities. For instance, using GNSS RTK (defined below) signals, the machines can automatically navigate the lanes and even perform headland turns. This allows for saving time in complicated manoeuvres and continuing work even in weather conditions with limited view.

Variable rate control enables a site-specific adjustment of input doses based on available

[1] See for instance the academic journal "Precision Agriculture" published by Springer https://link.springer.com/journal/11119), focussing only on crop production, in contrast to the most recent International Society of Precision Agriculture's (ISPA) definition https://www.ispag.org/about/definition) which was just revised to better reflect the convergence of precision livestock and crop farming technologies..

information about the field to be managed. Such information can be field topography, historical yields, soil properties, etc. For example, yield potential maps can be created which serve as a basis for prescription (or application) maps that determine the right amount of inputs, e.g. fertilizer, seeds or plant protection products to be applied for each location in the fields making use of GNSS-RTK georeferencing.

Section control allows for activating or deactivating specific implement sections during the application. This prevents redundant or missing treatments of the same spots due to non-ideal field geometries, leading to overlapping areas or gaps where the machine drives twice or never as a result of route planning. Again, based on predefined maps of the fields, section control allows for more precise application of inputs and thus higher input efficiency, contributing to reducing costs and negative environmental impacts.

All of these systems can be interpreted as digital assistance systems in agricultural machines. For more details, please refer to the textbook of Noack (2024).

What sets *smart farming,* the next step in the technological evolution, apart from precision farming is the increasing use of advanced information and communication technology, such as real-time sensor systems delivering more field and machine data. This data is further used for farmer decision support and even higher automatization during the actual work on the fields. Smart farming thus extends the toolbox of precision farming by the utilization of smart devices (sensors, on-board control devices, smartphones, etc.) and advances in communication technology, in turn allowing to acquire more, and make smarter use of, agricultural data. Up to this point, so-called prescription or application maps had to be designed beforehand on the computer by the farmer based on his knowledge about the fields and on conducted labour-intensive field sampling (e.g. soil parameter mapping through EM-38 sensors or nutrient availability through sending soil samples to a laboratory). These maps have then been manually transferred to the tractor for enabling variable rate and section control functionalities. This is still a common approach, however the use of real-time sensing on the fields additionally allows for in-situ adjustments of the complex machinery (i.e. tractor-implement combinations), which is for instance used in site-specific fertilization by sensing the biomass distribution of the plant stand (DLG-Ausschuss für Digitalisierung, Arbeitswirtschaft und Prozesstechnik and Griepentrog 2019).

Digital farming pursues exactly the same goals as precision or smart farming by continuing the application of their methods as developed so far, but extending the methodological repertoire by additional components. These components originate from recent advances in information and communication technology, i.e. the drivers of progressing digitalization. Among the most important digital technologies adopted for the digitalization of agriculture are (1) Internet-of-Things and smart sensors, (2) wireless and wired communication and network solutions allowing for machine-to-machine and machine-to-infrastructure communication, (3) edge and cloud computing providing computational resources for direct on-site or delayed off-site computations, and, (4) Artificial Intelligence (AI) that constitutes a central element for intelligent processing of the available farm data, decision-support on different horizons, and for achieving higher robustness and autonomy in agricultural machines (DLG-Ausschuss für Digitalisierung, Arbeitswirtschaft und Prozesstechnik and Griepentrog 2019; Basso and Antle 2020; Paraforos and Griepentrog 2021). These new digital technologies act furthermore as enablers for viable robotic or agentic solutions in agricultural settings, which are deemed to arrive at unpreceded degrees of autonomy in the near future. This means that autonomy will shortly not confine itself to individual agricultural machines or highly automated but still isolated process steps. Digital agriculture will allow autonomy to expand to the entire process, the farm, or even to inter-farm levels. We will get back to this issue in the last part of this chapter.

15.2.2 Available Digital Tools to Support Agricultural Production

We will now have a very brief look at digital tools that are already available to farmers these days. Utilization of such tools can lead to increased productivity and efficiency when managing and performing agricultural processes. They can further lower the burden of human operation when dealing with complex machines. For the sake of brevity, we keep the discussion of each short and refer the interested reader to the references as given at the end of this chapter.

- ISOBUS
  ISOBUS is a worldwide standard that physically and digitally connects tractors with various implements. It is defined in the ISO norm 11783. It not only defines the protocols for data exchange, i.e. which attribute in which data type can be read where on the bus. It also standardizes technical hardware specifications regarding the connectors as well as the user interface to control implements on an ISOBUS universal terminal in the tractor cabin. ISOBUS allows for more advanced communication and control functions on agricultural machines such as Tractor-Implement-Management (TIM), where the tractor is controlled by the attached impalement, e.g. the adaptation of the working speed. Cf. also Mottram (2022), Agricultural Industry Electronics Foundation e.V. (2024).
- GNSS-RTK
  The Global Navigation Satellite Systems (GNSS), depending on the region, also broadly known as GPS (Global Positioning System), allow for positioning agricultural machines. When tractors are equipped with GNSS/GPS, input applications (fertilizer, plant protection products, etc.) or other sensor measurements can be georeferenced with a meter-scale precision. When the Real-Time Kinematic (RTK) technology is combined, the setup needs an additional reference station and correction signals (e.g. from mobile networks) but then allows for centimetre precision. This is, for instance, utilized in autonomous steering systems for tractors or high-precision sowing and intra-row weeding of sugar beets in robotic systems. Cf. also Herlitzius et al. (2022), DLG e. V. (2016), Brandenburg (2024a).
- Telemetry/Telematics
  Telemetry is a technique to measure certain machine parameters in real-time and send the data to a spatially different location, such as the manufacturer of the machines or fleet management solutions. This technology is also termed telematics by some manufacturers of agricultural technology. It allows, e.g. for fleet management, agricultural process monitoring, or early detection of wear and in turn predictive maintenance. Combined with the GNSS-RTK data from the machine, the remotely measured data is available in georeferenced form (Brandenburg 2024b).
- Agricultural Information Systems
  Farm Management and Information Systems (FMIS) are application software products that aid farmers in their daily work. As information systems, they provide tools for data collection and visualization as well as decision support. They further allow for measurement planning and creation of prescription/application maps, which can be transferred to the tractors for site-specific operations or variable rate control. Most FMIS incorporate Geo-Information Systems (GIS). These visualize the farmer's fields and set the geocoordinates of the land. This allows for field-specific measurement documentation and, thus, support compliance with legal requirements. Next to FMIS for crop production, variants for herd management exist. Another type of agricultural information system is fleet management systems, which monitor the work performed by the agricultural machines of a farm holding or contractors and give insights in the utilization efficiency thereby allowing for cost optimization. Cf. also Mottram (2022), Fountas et al. (2015), Wagner (2024).

- Digital Services (e.g. Weather, Market data)
  Next to information systems usually accessible via the farmers' computers, more digital services are available that enable decision support. For example, websites providing regional weather information and forecasts are of utmost importance to plan agricultural measures. Market prices can be monitored using other websites or news feeds (e.g. the ► Agri-food Data Portal). Pest and disease monitoring services (e.g. the ► ISIP or the ► AG PEST Monitor) allow the farmer to observe the risk of infestations and perform prevention. Most of these digital services are already delivered to the farmer's pocket via mobile apps.
- Mobile Apps
  This leads to the next category of already available digital tools, namely the use of mobile software applications (short `apps'). These apps are usually runnable on mobile devices such as smartphones or tablet computers and thus can be easily brought to the field, barn or to any other place where it can be of help to support farmer decision making. Examples comprise scouting apps for detecting e.g. the presence of weeds, pests or other stresses (diseases, drought, etc.) in plant stands directly by taking photos in the field. These usually can give recommendations to the farmer what measures to apply to effectively counteract weed pressure or protect the plants' health. A more simplistic example is an app that simply helps to identify and categorize crops' and weeds' phenological stages by showing example images along with relevant information such as the growth stages, typical plant morphologies or appearance in the presence of diseases such as yellow rust. Apps for planning and documentation of agricultural measures on the field are of high value and increase farmers' efficiency.
- Chatbots and other Generative AI-Based Solutions
  Since the inception of ChatGPT, a chatbot heavily based on an AI technique called Large Language Models (LLMs), many industries, public and private sectors, as well as the academic system, are hit by the Generative AI wave. These bots were trained on a massive corpus of human-created content (websites, books, scientific papers, laws, etc.) and, to this end are capable of producing human-mimicking text and hold conversations based on so-called `prompts' as passed by a human user. First agricultural chatbots are either announced by global agricultural companies or already explorable on the web (e.g. the AgriGPT project). The idea is that this system is `fine-tuned' or `aligned' to an agricultural context so that farmers can prompt any question related to agriculture to the system. Also, start-ups are forming which provide solutions relying on LLMs-based technology to aid farmers decision making and ease their daily work life. The idea is that of a `Co-pilot' for farmers that can take either chats, spoken words or captured images (multi-modal input) to support agricultural management, such as automatically completing documentation or requesting missing details. It thereby can also learn to adapt to the farmers' individual needs and eventually can save farmer's valuable and limited time.
- Agricultural Robots
  Finally, what usually comes to mind when thinking of digital agriculture is the use of agricultural robots. We subsume unmanned ground vehicles (UGVs) and airborne unmanned aerial vehicles (UAVs, often called `drones') under this category. These systems are equipped with sensors to perceive their environment (e.g. soil conditions, crop rows, weed pressure and other environmental factors), a computing unit to process, fuse or simply transmit the sensed data or to directly derive control actions, and actuators that are then activated in certain situations to modify the physical environment via so-called end-effectors. Possible end-effectors comprise e.g. blades for cutting unwanted arable plants (weeds), nozzles to spray plant protection products to targeted plants, or grippers to pick fruits during harvest.

Agricultural robots can broadly be understood as tools for automating agricultural processes, i.e. on the fields but also indoors for animal husbandry processes (automatic forage robots, floor-cleaning robots, milking robots). Depending on the degree of a) necessary farmer involvement and b) decision freedom by means of artificial intelligence, we can further differentiate between autonomous or even intelligent robots.

15.3 Artificial Intelligence in Digital Agriculture

It is indisputable that *artificial intelligence* (AI) is one, if not the most disruptive technology these days. With the tremendous advances in machine learning and its application in predictive modelling, computer vision and natural language processing, AI strongly contributed to groundbreaking technological innovations of the last decade, finding their way in domains such as autonomous driving, medical research, personal or corporate AI assistants and many more. Also, agricultural production has to be mentioned here, even if the adoption of AI in agriculture is still in its infancy.

> ***Artificial Intelligence*** is not straightforward to define. Several attempts from different disciplines exist. AI is a scientific discipline originating in the computer sciences that deals with the development of methods and algorithms that imitate natural intelligence and human cognitive capabilities, such as reasoning, planning, learning or the like in order to solve human-set goals (Copeland 2024). Prominent (subsymbolic) methods of AI comprise deep learning, generative models such as large language models and deep reinforcement learning (see ► Sect. 25.1). But also inference systems building upon rule-bases that capture expert knowledge and other symbolic approaches for efficient search, planning, recommendation and decision-making still belong to the field.

Excursus 15.1 A Definition of Artificial Intelligence from the European AI Act

A recent definition in the newly enacted AI Act defines an AI system as 'a machine-based system that is designed to operate with varying levels of autonomy and that may exhibit adaptiveness after deployment, and that, for explicit or implicit objectives, infers, from the input it receives, how to generate outputs such as predictions, content, recommendations, or decisions that can influence physical or virtual environments' (European Union 2025). In recital 12 of the European law, it is further specified which techniques are considered part of AI. Among them logic and knowledge-based approaches and machine learning, allowing the machine-based systems to infer, predict, analyze, and generate new output. The several degrees of autonomy refer to the extent to which human oversight is (still) required. AI systems need to exhibit adaptivity to allow for continual change during their productive use and utilize e.g. self-learning mechanisms to accomplish that.

A more simplistic (and abstract) view on AI is to imagine it as any kind of software that leverages specific types of algorithms that monitor and process collected data to derive certain outputs that support the users. This can be a classification of a plant or its health status using a smartphone app. It can be a software running on highly efficient computing devices embedded in machines, e.g. a camera unit attached to a robot to detect and localize weed plants on agricultural fields. AI can also be incorporated at higher levels to aid farmers in planning their activities. It can be integrated in FMIS to analyze the data available for the past years to predict yield potential or spots with high risk of crop disease occurrence and spread. There are plenty of further use cases where AI already strongly aids farmer decision-making through recommendations or automated action planning. For more examples on the potential of AI in agriculture, the reader is referred to recent review articles, e.g. Osinga et al. (2022); Ayoub Shaikh et al. (2022); Khanna et al. (2024).

First commercial applications are successfully entering agricultural practice. A currently highly prominent example is AI-supported weed control. Unmanned aerial vehicles (UAVs, often simply called `drones') are used to fly over entire fields and, by means of using high-resolution cameras, are able to detect spots where weed is present between the cultivated plants. In a succeeding step, the exact positions are determined by georeferencing the drone-images with available GNSS-RTK signals and prescription maps for highly precise application of herbicides through conventional mechanization (tractors plus sprayer) are created. Another way is to perform all of this in only one step. This means equipping the machines with cameras and computing devices running AI software to detect and treat the unwanted arable plants directly.

Think out of the box. Imagine your personal lives, and try to imagine where AI technology already comes into play. This can be at home, during a holiday trip, or at work. Just think of your technical devices and the services/functions they offer and how you interact with them. You might be surprised, what a `professional' AI user you already are.

Contemporary AI solutions are mainly based on deep learning, an approach to enable machines to learn from data using so-called artificial neural networks. Deep learning thus constitutes a subcategory of machine learning and therefore constitutes a data-driven approach. This means that data is the central asset here. Data needs to be collected in vast amounts to train powerful deep learning models. Collected data, however, needs to fulfill some requirements, i.e. it needs to be of high quality, representative for the task to be learned by the AI, and, in case of supervised learning tasks (see ▶ Sect. 25.1), needs to be annotated by human domain experts. This demands for high efforts to collect, prepare, curate and finally annotate the data, all before it is fed into machine learning models for the actual task, for instance predicting yields of a certain region based on weather data and historical records. Data can be collected using sensors e.g. on agricultural machines, UAVs or satellites, can be retrieved from recordings and documentation of agricultural activities necessary for regulatory compliance, or gathered from publicly available databases and repositories (More possibilities exist, of course).

Now that we have gained a basic understanding of the term AI and have seen some examples of its use in crop production, we want to take a step further and differentiate a bit more by introducing the concept of *Intelligent Agricultural Technology*. Let us first take an attempt for its definition along with some classification criteria, which are deemed

necessary to qualify agricultural technology as *intelligent*.

> ***Intelligent Agricultural Technology (IAT)*** describes technical systems designed for the purpose of planning, performing and optimizing agricultural measures within agricultural processes without the need for immediate human intervention. IAT systems are thus autonomously acting systems, which integrate one or more constituent AI software programs (also called *agents* in the AI context) via computational units with hardware components (e.g. robots or other mechatronic systems). The embedded AI agents enable the resulting cyber-physical system to continually perceive its environments (e.g. soil conditions, vegetation status) through sensors and other information sources (e.g. weather forecasts) as well as to react through immediate self-adaptations or planning the best next actions in order to optimize the system's utility (e.g. area output, input efficiency, expectable yield). Actions can be either internal adaptations of machine parameters (e.g. working speed, engine speed), signals to control effectors that modify the environment (e.g. harrows, hoes, grippers for fruit harvest), or recommendations to be realized by the farmer.

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To keep the definition above as concise as possible, we did not further differentiate between cyber-physical and purely virtual systems, the latter for example being an FMIS or mobile app. Nevertheless, it should be emphasized that such information systems primarily working in the virtual (or cyber) sphere (i.e. have no physical counterpart besides the computer they are running on), would still fall entirely within our understanding of IAT.

With that in mind, we now detail our definition by declaring three important properties an IAT system should possess. These are:

- *Adaptivity* to continual changes as observed in the spatio-temporally highly variable agricultural environment
- *Robustness* against unexpected disturbances in the agricultural process, its environment or within the involved machines themselves
- *Flexibility* to abrupt or more gradually appearing changes in the system's short- and long-term goals or overarching boundary conditions

By means of leveraging AI methods, IAT systems can be endowed with these properties. Machine learning allows a system (being it an autonomous robot for weed control or an information system predicting agricultural key performance indicators) to continually self-improve based on new experiences gathered during operation time. Pattern recognition, data modeling or anomaly detection allow for observing internal system states and detect deviations from ideal conditions which in turn can trigger countermeasures to recover to a target corridor of system utility. Such utility declines could be due to sensor failures or drift, the need for route recalculation due to unexpected obstacles on the pathway, etc. Efficient metaheuristics for multi-criteria optimization provide a means to weigh potentially competing sub-goals or maintain a repository of previously effective control policies to quickly adapt to changing circumstances, e.g. due to changing weather forecasts, delays in operation time on the fields or supply of inputs.

IAT is therefore deemed to become a central element in the further evolution of agricultural production. It will pave the way for highly autonomous operations on the fields, but also on higher technological levels such as the whole farm level or even across farms. The overarching goal of IAT is to simultaneously increase the efficiency, sustainability, as well as resilience of agricultural processes through the targeted utilization of AI and digital technology.

In the near future, realisations of IAT are envisioned to manifest in intelligent mobile robots fully autonomously conducting field operations, and subsequently entire agricultural production processes. Furthermore, powerful digital platforms will increasingly offer farmers easy access to AI-powered digital services at their fingertips, capable

of automatically adapting to their individual farm data.

One might ask if IAT is not already here. What about the numerous apps, software applications and autonomous robots we can see in the media, at experimentation farms or already in real practice? At this point, we should confess and recap that already the definition of AI is anything but trivial. Tailoring this concept to agricultural technology complicates it even further. To illustrate this, let us run through another example:

- Consider a conventional tractor with a sprayer attached to apply plant protection products on a crop field. The sprayer is capable of spot spraying, another smart farming technique that allows for precise application to individual arable plants. Therefore, it uses multiple cameras with computational units to detect and localize weeds and based on that opens the corresponding nozzle to apply the herbicide. The weed detection is realized by using an efficient deep learning-based AI-model. We should now think of our three properties as defined before. Is this system adaptive, robust and flexible? Well, for this we need to know more about the internal workings and algorithms deployed. But this makes up a good exercise. If there would be only a static weed detection model that simply outputs the coordinates of every detected weed and then automatically opens the sprayer nozzle for this row, but does not consider economic thresholds (see ▶ Sect. 6.11.1 on farming concepts), we would maybe not consider it flexible. If the system works only for weeds typical in winter wheat or other cereals, but has no mechanism to switch its model automatically when used in a sugar beet field, can we state that it is adaptive? Rather no. If the model's detection performance drops tremendously if the sunlight shines in a way that shadows appear that were not present in the training data of the AI-based detection model, or if the detection rate drops when we are faced with fog or another soil type, would this system qualify to be considered robust?
- With all these questions answered with `no', we could conclude that it is not an IAT system, but still a smart farming system employing real-time sensing to enable section control.
- This example should illustrate that not every system that seems to exhibit some level of intelligence really qualifies as an intelligent system. Isolated AI components rarely achieve the requirements of adaptivity, robustness and flexibility. IAT systems therefore need to integrate multiple AI software components into an intelligent system architecture that establishes a feedback control loop with reflection capabilities regarding the system's utility.

15.4 Looking Ahead: The Role of AI-Supported Digitalization in the Bioeconomy

After having discussed some of the most prominent digital technologies used in today's agricultural primary production processes and after diving a bit deeper into the topic of AI in agricultural production, we now take a bird's-eye view on how these digital technologies can aid the transformation toward a bioeconomy.

Consider ◘ Fig. 15.2, where a simplified agri-food value chain is depicted. For our purposes in this section, let us directly zoom into the second part of the depicted chain, namely the agricultural production and leave the sector providing inputs, such as fertilizer or fuels, aside for now. The primary agricultural production entails processes leading to material flows that are arranged in a circular fashion (see next paragraph). To this end, we already envision a single future farm as a circular system with `openings', that is, material (residues, biomass, etc.) and product flows (milk, harvested fruits, biogas, etc.) outgoing to other parts in the value network. In the figure, two possible downstream links are exemplarily depicted: (1) A link to the bioenergy chain, where biogas (methane) can be finished to e.g. biofuel or processed to renewable energy for charging electric cars. (2) A second link shows

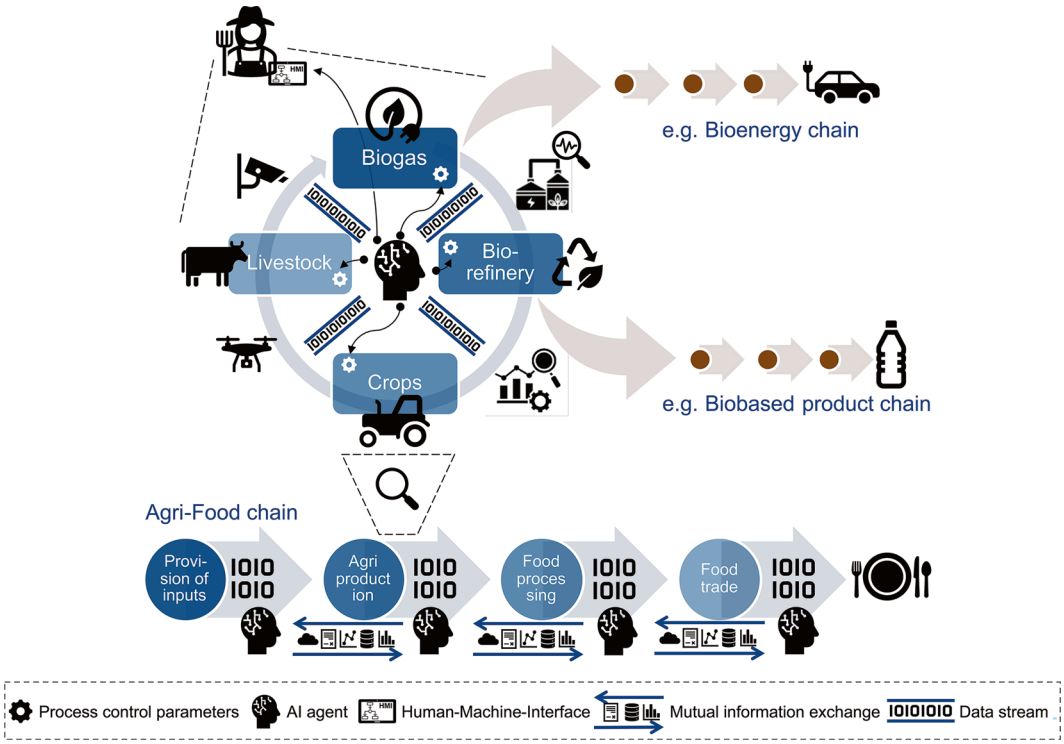


Fig. 15.2 Schematic illustration of the points of impact of digitalization and AI in a bioeconomic value network. (© Anthony Stein)

the input (such as platform chemicals) from the agricultural production to a value chain for bio-based products, i.e. products not based on fossil resources, such as `bioplastic' bottles (see ▶ Chap. 19 for more information). A further example would be a classical agri-food chain comprising manufacturing companies, potentially prior food upcycling stations, logistics businesses for delivery, up to retail and eventually the customer's `fork'. Even streams to other instances in the agricultural (primary) production sector are possible, e.g. to other farms or conversion facilities further processing the residual materials such as manure or biomass from the originating farm's production processes. The latter aspect highlights the decentralization of the agricultural system – an aspect that also has deep impacts on the engineering discipline of developing digital tools and AI solutions for a digitized agriculture.

The agricultural production sector thus can be seen as a system of autonomous entities – for simplicity, we only consider these entities as farms for now – that produce materials and products in a bioeconomic, i.e. circular fashion. One example of such a farm entity is depicted in Fig. 15.2: A mixed farm holding that manages both animal husbandry and crop production, but also runs a biogas plant and (co-)operates a decentralized biorefinery plant (Dahmen et al. 2019; Świątek et al. 2022). For a more detailed description of this on-farm biorefinery concept, please refer to ▶ Sect. 23.3. In our example, imagine a very simplified circular production flow: Crops are produced to feed livestock. Livestock (e.g. dairy cattle) produce milk as a product and manure as a residue. Both the remaining biomass from fields and manure are fed to the biogas plant, producing methane, which can be converted to energy. This energy is used to supply the farm including the decentral biorefinery plant. The latter again has residual materials that can be fed back to the biogas plant. Next to the internal cycle, the outgoing links as mentioned above connect individual actors to different branches in the value network. Such a diversification of

production streams contributes to the establishment of a circular production chain. It also paves the way to establish more than one income flow.

With this illustrated example of a circular agricultural production system as part of the underlying agri-food chain in mind, Fig. 15.2 further gives an idea of which points of impact in the bioeconomic value network exist where digitalization and AI can and most probably will take effect. On lower technological scales, data will be collected by (smart) sensors such as cameras carried by agricultural robots (UGVs and UAVs) navigating fields or in barns where animal husbandry takes place. AI will be employed to draw timely insights from these data streams. Biogas plants and biorefineries can further be instrumented with a variety of sensors in order to feed process monitoring and control systems that give insights into the process efficiency (and productivity). Upon that, AI will optimize these processes by means of enabling higher degrees of automation. Utilizing new end devices and forms of *Human-Machine-Interfaces (HMI)* allow the farmers at every time to inspect their agricultural processes' states and quickly recognize potential disturbances. AI-based chatbots can further contribute to easy-to-use and interactive HMI interfaces where the farmers (or machine operators) can simply ask the AI for receiving relevant information in natural language. Moving on to the level of the overarching value network, progressing digitalization of the involved sectors will pave the way for data and derived information being securely shared among the participating and trusted parties. The technology behind agricultural data spaces (Kalmar et al. 2022) is one possibility that fosters the connection of previously prevalent data silos while preserving data sovereignty (Boye et al. 2023). This, in turn, would allow the AI to leverage the resulting linked data and information flows to enhance inter-company supply chain optimization. Such data linking along the value network further paves the way for data-driven sustainability assessments and traceability aspects, which are deemed to play an important role for customer acceptance aspects in the future.

From a systems thinking perspective, looking at the possible links (both physical material flows or virtual links via data) among multiple actors of the agricultural production sector itself, but also the outgoing links to downstream parts of the value network, this results in a complex interwoven system which cannot be properly managed by single human entities anymore. Thus, viable approaches to manage these systems and the resulting data ecosystems need to be developed to master this complexity.

Potentials and Promises of AI-Enhanced Digitalization

This is where the promises of AI-enhanced digitalization can materialize. The emerging complexity due to decentrally organized but interacting actors in the agri-food system, all having some connections to succeeding (and presumably also preceding) actors in the value network, is hardly manageable by central authorities or individual persons. Digitalizing the underlying production and business processes in principle allows for continual monitoring and – when done the right way – for highly interoperable and sovereign data exchange among those actors along the value network. As illustrated in Fig. 15.2, each of the process steps is equipped with digital tools that collect corresponding process data. This allows the involved most critical steps to be accompanied by a digital pendant (sometimes called a digital shadow in the Industry 4.0 literature) that represents the relevant data for the individual stage. This holds true for the individual circular production processes on farms, where e.g. UAVs monitor fields, cameras observe the behaviors of animals, or autonomous robots take over laborious agricultural work, what can lead to higher process automation and can therefore compensate for labor shortage. It also holds for the overarching stages in the value chains, where for instance reports from supply and demand analyses between food manufacturers and food trade can be utilized to digitally connect these actors for mutual process optimization. On both granularity levels, the instrumented processes can be monitored by means of sensors or contextualized information derived

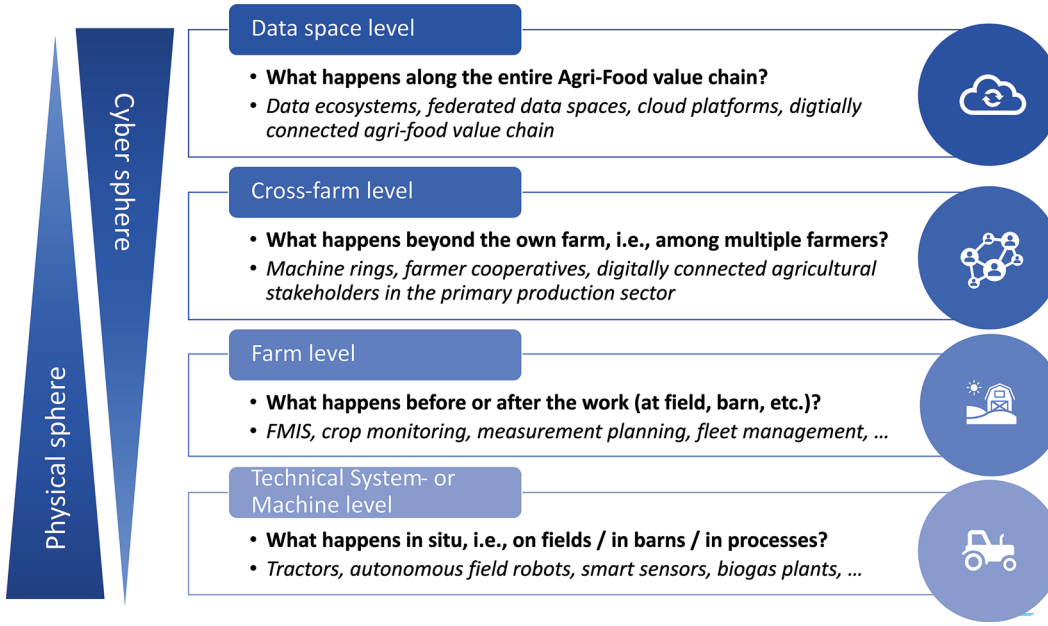


Fig. 15.3 Schematic of several technological levels of a digitized agricultural production. (© Anthony Stein)

from the sensed raw process data. Information systems can be deployed to derive the relevant information and further process it to create actionable knowledge for later process control. The actual control step can be done either by humans or – what due to the complexity and information amount seems to be more realistic and viable – by AI. To this end, we can build and distribute AI software (so-called `agents'), optimizing specific (sub-)systems and processes of agricultural production, along the value chains. Following the layered illustration in Fig. 15.3, such AI agents can, for example, work on the level of technical systems (or the *machine level*), e.g. to control autonomous robots navigating crop fields (single machines, or an entire swarm of robots), to adaptively monitor animal welfare, or in form of intelligent control systems managing a biogas plant. Taking one step to the next technological level, AI agents could further be employed on the entire *farm level.* For instance before or after the in situ work for planning or automatically documenting the agricultural measures using intelligent FMIS. Such intelligent agents could also automatically incorporate relevant information such as weather forecasts or market prices from the *data space level*. Other examples at the farm level comprise optimization of routes for autonomously driving machines to fields and distribution of the work in the fields, management of stock or the ordering of input materials. In consequence, intelligent decision support can be enabled by obtaining a spatially and temporally highly resolved picture of the crop/livestock status from the lower technical level. At the *cross-farm level,* AI-enabled possibilities comprise autonomous rental of required agricultural machines from machine rings, including negotiation in case of conflicts with other requesting farmers, as well as solutions to efficiently share machines directly in farmer cooperatives, thereby increasing the overall machine utilization. Another considered technological level is the *data space level*. Here, the transition from the physical to the cyber-sphere comes to a maximum. At this level, data ecosystems evolve around cloud platforms offering digital services, which allow to automatically and safely exchange data, information and computer-representable knowledge in a federated and data sovereign manner. Future AI agents

operating on this level will leverage these data products to optimize supply chain processes across the value network with the overall goal to increase the agri-food system's and neighbouring sectors' process transparency, resilience and sustainability.

Obstacles and Challenges

On the downside, as for almost any sector hit by the digital transformation, typical challenges must be solved first, before far-reaching value can be created. Often discussed obstacles comprise concerns regarding data privacy (e.g. company secrets, sensible data), lack of standards to establish (data) interoperability, as well as reluctance and missing trust in regard to using new digital technologies. Farmers are uncertain about with whom to safely share potentially sensible data, especially if it remains unclear who is actually profiting from it and for what other, so far not anticipated purposes, the data might be used in the future. Regulations such as the ► European Data Act make up the first legal treatments in that direction. Cloud-based platforms promising data sovereignty (user-defined access control, data security and transparency what happens with the data) emerge, that enable bringing together digital service providers with data producers and holders. Furthermore, agricultural data spaces are under construction, which attempt to safely connect data silos in the data ecosystem evolving around a digitized agriculture by means of employing federated services, which again will be accounting for aspects such as data interoperability and data sovereignty.

Moving back down from the data sphere to the more physical levels (cf. ◘ Fig. 15.3), the corresponding challenges also become more physical. A resilient information and communication infrastructure is needed to bring AI-based digital solutions to the producing farms. Connectivity is not assured in every region, so alternative ways to transfer data among cooperating technical systems as well as to utilized farm information systems, such as LoRaWAN or other ad-hoc networking technologies have to be considered as fallback solutions. Computing power `on the edge', e.g. realized by small-scale servers installed at the farms, can aid to increase technical resilience by preventing full dependence on internet connectivity and cloud-based services. This, however, entails investments for which the actually achievable value has first to be absolutely clear to the end-users.

Accordingly, future generation farmers, agronomists, agricultural engineers and further actors must be set in a position to understand both the chances but also the accompanying obstacles of these new digital technologies, what allows them to thoroughly consider whether investments will pay off. This can be achieved by agricultural consulting companies or extension services that – together with the farmers – analyze the farm-individual potentials and upon this derive actual needs for digital and intelligent agricultural technology. On the other hand, digital and data literacy must be established early in the existing agricultural career paths what is later expected to lead to increasing understanding of the potentials, higher degrees of trust in the new technologies, and strong advancements of domain-specific solutions from the domain experts themselves, what, in turn, might ultimately result in higher adoption rates of digital technologies in agricultural production.

This chapter constitutes a brief introduction to the broad and diverse topic of digitalization in agricultural production. Accordingly, we could only scratch the surface on various topics, what was intended to help the reader to dive deeper into the topic on its own during further self-study. There exists recent literature that allows a more comprehensive entry into digital technologies for sustainable agriculture – as one essential chain link in the overarching agri-food value chain and, thus, of bioeconomy.

In Dörr and Nachtmann (2022), the editors provide the interested reader with a comprehensive handbook to obtain an overview of the diverse topics of digital farming. Many contributing experts from industry and academia are sharing their knowledge ranging from rather technical to law perspectives in this field.

In another textbook on Digital Agritechnology (Mottram 2022) a certain part is explicitly devoted to digital livestock farming applications, another important field that we needed to omit here for the sake of brevity.

Lastly, the second edition of another textbook edited by Patrick Noack (2024) provides another valuable resource for getting an overview of methods and applications of agriculture 4.0 (yet another term of digital agriculture often used synonymously).

In general, a vast number of research articles was published in the past about this groundbreaking technological innovation, which is shaping the future of agricultural production and bioeconomy as a whole. The aim here was not to survey all of these articles. Still, in the literature references the reader finds some recent works to topical discussions and is encouraged to take a closer look.

Questions

1. In this section, we focused on digital technology in biomass production and discussed the terms precision, smart and digital farming. Now consider the field of `livestock farming'. Imagine the potential of digitalization and AI in animal husbandry. For each technological level as depicted in Fig. 15.3), what application of digital technology could be beneficial for the farmer?
2. Is an autonomous robot operating on a field always embodying artificial intelligence? Give relevant properties of intelligent agricultural technology and apply them to the example of a driverless tractor robot using GNSS-RTK technology to autonomously navigate the routes preplanned by the farmer in his farm management information system.
3. Data was discussed as being the `fuel' for AI applications. What problems with data can you imagine in a highly decentralized system such as agriculture or even the entire value chains in a bioeconomy? And what role does the concept of data interoperability might play in that regard?

Answers

1. On the technical system level, cameras (RGB and/or thermal) can be installed to allow for a continuous situation monitor in the barns. Based on this image or video data, AI can be utilized to e.g. detect anomalous animal behaviour.

   On the farm level, process indicators can be derived from the sensor data that allow insights on the performed husbandry processes what in turn might reveal potential for process optimization or enables direct support for farmers' decision-making.

   On the cross-farm level, farmers can engage in data federations with the goal to collaboratively train machine learning models. Each participating farmer's shared data reflects individual local conditions what benefits the AI to reach higher levels of robustness and in turn overall predictive accuracy. Furthermore, an AI system could coordinate management processes what allows for improved sharing agricultural machines among neighboring farmers.

   Lastly, on the data space level, process indicators and production information derived from data sensed in situ can be passed to subsequent chain links in the agri-food value chain. For example, information of the milk production process such as milk quality and composition or other product properties and characteristics. This information can then be used by the food manufacturer to better control the refinement processes. If information on the production processes is even further passed along the chain, traceability of the food production process 'from farm to fork' can be established for the customer (Krupitzer and Stein 2024).
2. No. Whether an agricultural field robot can be considered `intelligent' depends on various factors. In this chapter, we focused on three properties that qualify agricultural technology as an intelligent system: robustness, flexibility and adap-

tivity. If the tractor or robot is solely reliant on the GNSS-RTK technology for navigating the field, it can hardly be seen to possess any of these. In case the GNSS signal is lost (disturbance), the self-driving machine is not able to position itself anymore. For instance, in the case of automated weeding, if a robot does know the exact position of each georeferenced crop plant but lost track of its exact own position, and still continues hoeing, the risk of damaging crops is high what negatively impacts the system's utility in terms of quality of work. Such a system would become more robust if it had a fallback technique to detect crop rows and weeds, e.g. using on-board cameras and AI, and thus would still be able to navigate, however potentially at the cost of a reduced weeding precision. Flexibility depends on the degree of autonomy. Is the robot capable to optimize or re-plan the predefined routes during operational runtime on the field? If yes, it would be able to automatically react to e.g. depletion of remaining energy or seed tanks by adding logistic stops to the routes or even by making use of field topography. In case of suddenly changing weather conditions, a flexible robot could decide to adaptively increase working speed to achieve higher area capacity and finish the field at the expense of sacrificing quality of work. Adaptivity lets intelligent systems identify the need for and perform adjustments of its adaptable parameters and components. In case of an autonomous tractor-seeding combination, adaptivity would enable the system to perceive current soil conditions (e.g. through the use of a stereo camera or tactile sensors) and as a response vary the seeding depth or intensity of reconsolidation.

3. Data can possess various problems. Data can be incomplete, what means that values of specific attributes in the data set are missing (e.g. due to clouds covering relevant areas in satellite images or missing soil sensor readings at relevant points in space or time due to sensor failures). Data can also be non-representative, i.e. the exemplary training cases used to train AI models are idealized (e.g. from an experimental laboratory setup) and do not reflect the real-world circumstances the trained AI model would face in practice properly. Controllers for mobile robots to navigate through maize rows trained in 3D computer simulations usually will not be directly applicable to real robots operating in real fields. In situ collected data can simply be too vast, i.e. the amount of available data is too large to be processed at once on a certain type of resource-limited computing device. If data volume is too large to be processed on embedded devices, the transmission to a computationally more powerful cloud service on the other hand might lead to latencies that are considered unacceptable to meet real-time criteria. Efficiently processing for instance high-resolution 3D-depth images of a robot's surroundings can already be challenging if the required frequency of image capturing, as partly determined by the robot's speed, is too high. Next to these general data issues, we now look at the aspect of the agricultural system's decentralized nature. This leads to what is often called a high degree of heterogeneity, which naturally manifests in the collected data, too. Local site conditions vary strongly due to spatial and temporal variability of the agricultural production system. This has an impact on the creation of high-quality data sets, which are needed for obtaining robust AI models. Such AI models, utilized for whatever purpose (e.g. yield prediction, weed or disease detection, animal behaviour recognition), are supposed to work reliably under various of such conditions. This, however, necessitates for a properly created training data set that ideally incorporates any of these conditions in a sufficient amount. Or put in another way: An AI model that works on a robot on a farm A should also work on a farm B without the need for labori-

ous recalibration. AI methods that deal with this issue are subject of current research. Proposed solutions range from synthesizing training data using Generative AI, over employing photo-realistic simulations to create training data sets, to aggregating AI models trained locally at various sites having different conditions. A more detailed discussion, however, falls beyond the scope of this chapter. We can see how these data problems unfold already in the agricultural sector. However, this becomes even more intricate if we look along the value chains in the bioeconomy which are spanning multiple elements of the chain. Now data must not only be representative for the conditions of several local actors sharing a common task. When shared across sectors and companies, the data must be readable, interpretable and processable for the different information systems importing them. Achieving this form of data interoperability is a difficult challenge to be met, since different parties have to agree on common data formats, exchange protocols and interfaces, as well as to vocabularies and semantics to describe relationships between entities as present in the data. This interoperability of data is thus an important prerequisite what paves the way for leveraging the potential of digitalization across actors in the value networks within a bioeconomy.

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Economics of Primary Production

Christian Lippert



Fig. 16.0 About ▶ Chap. 16—economics of primary production. (© Christian Lippert) (▶ https://doi.org/10.1007/000-htv)

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When developing new bio-based products and when trying to assess their market opportunities, it is indispensable to correctly calculate all expected unit costs. In this context, the provision for natural resources from primary agricultural or forest production is an important cost component. As all renewable natural resources need a certain time to grow, one needs to calculate the related capital cost and model biological growth over time to correctly account for all external and internal net benefits from natural resources. Furthermore, especially for permanent crops and woodland resources, corresponding biological growth expectations are to be combined with investment appraisal to derive optimised single and infinite rotations for different kinds of plantations. In other words, in this chapter we need to introduce both basic concepts dealing with interest calculation that is based on the existence of (economic) *capital growth* and with *biological growth*. Thus, ► Sect. 16.1 outlines basic concepts from compound interest calculation (i.e. capital growth) and illustrates reasons and ways of discounting, whereas ► Sect. 16.2 deals with simple ways to mathematically describe and simulate biological growth. Combining both approaches enables us to plan optimum resource use over time: in this context, we will identify optimum harvest (or rotation) times in forestry (► Sect. 16.3) and determine the optimum replacement time for permanent crop plantations that continuously yield yearly benefits (see ► Sect. 16.4). Our analysis will focus on private wood and crop related benefits. However, in ► Sect. 16.3 we will also briefly discuss how the inclusion of forest related positive externalities due to regulating or cultural ecosystem services will affect harvest decisions and optimum forest use over time.

Learning Objectives

After studying this chapter, you will…

- …be able to describe the fundamentals of investment appraisal and apply them with special regard to farm and forestry economics (see ► Sect. 16.1).
- …be able to model biological growth by means of the *Euler method* and analyse the results (see ► Sect. 16.2).
- …be able to combine and apply simple biological growth models and investment appraisal to design and optimise single and infinite rotations for different types of plantations (see ► Sect. 16.3).
- …be able to determine the optimal replacement times for long-lasting assets in agriculture and horticulture (see ► Sect. 16.4).

16.1 Investment Appraisal (Capital Budgeting)

In real life, every resource use results in an intertemporal sequence of benefits (B_t) and costs (C_t). In this context, a net benefit of a given amount of money is usually considered the less valuable the farther away in the future it is supposed to occur. Thus, one needs to compare future benefits (B_t) and costs (C_t) with present ones (B_0 and C_0). The standard approach to make future net benefits equivalent to present net benefits is to **discount** the former by multiplying them by a so-called **discount factor**. Whenever diminishing an expected future amount of money by means of discounting, this involves accounting for possible capital growth because the present value of this future amount is the money that one would need right now (as initial principal sum) in order to obtain the given future value as the initial principal sum plus the accrued compound interest. Discounting can be performed either assuming a discrete process (as illustrated in ► Sect. 16.1.1) or a continuous process (as illustrated in ► Sect. 16.1.2) in time. In ► Sect. 16.1.3, using the example of electricity production, we will briefly illustrate how to correctly calculate per-unit costs (in this case, costs per kilowatt-hour of electricity) when the relevant cost components are unevenly distributed over time. Finally, in ► Sect. 16.1.4 we will discuss the implications of discounting when environmental externalities are to be included in cost-benefit analysis.

16.1.1 Basic Notions in Case of Discrete Discounting

Assuming a discrete process with time steps of 1 year corresponds to the common approach in the banking business. Future net benefits or cash flows (B_t—C_t) are transformed into present values by multiplying B_t—C_t by a **discount factor** $\mathbf{(1+r)^{-t}}$, with r being an interest rate that reflects the opportunity cost of capital. Opportunity costs are the benefits foregone from a hypothetical alternative use of the capital invested in the project considered. If the money had not been invested in this project, it could have been placed alternatively at an interest rate r. Only when discounting, future cash flows can be compared to present cash flows (B_0—C_0). The discounted present value B_0 of a benefit B_t arising at the end of year t is given by

$$B_0 = \frac{B_t}{(1+r)^t} = B_t (1+r)^{-t}. \tag{16.1}$$

Usually, the so-called **discount rate** $\boldsymbol{r}$ to be chosen by the decision maker is the interest rate at which loans could be raised or the rate at which own capital (equity) could be placed, or a weighted average of these two interest rates (the weights corresponding to the shares of loans and equity used when investing). For example, assuming a discount rate of r = 2% the present value of an expected benefit of € 100 in t = 5 years is $B_0 = B_t (1 + r)^{-t}$ = € 100 $(1 + 0.02)^{-5}$ = € 100 • 0.90573 = € 90.57. In this case, 100 Euros available in 5 years have got the same value as 90.57 Euros today. In other words: one would have to place 90.57 Euros today at a rate of return r of 2% in order to obtain a benefit of 100 Euros in 5 years.

For simplicity assuming in investment appraisal that all yearly benefits B_1, B_2, ..., B_T and all yearly costs C_1, C_2, ..., C_T related to a certain project are **payments in arrear**, which means that in each case they occur exactly **after** $\boldsymbol{t}$ **years** (t = 1, 2, …, T), whereas the benefit B_0 and the cost C_0 are to be obtained or to be paid right now, the **net present value (*NPV*)** of the project is

$$NPV = \sum_{t=0}^{T} (B_t - C_t)(1+r)^{-t} \tag{16.2}$$

As a general rule, a project can only be worthwhile as long as its NPV is positive. If the *NPV* is negative, this means that the project is unprofitable. Of course, the NPV strongly depends on the assumptions made regarding the discount rate r and when calculating the net benefits B_t—C_t. Therefore, careful sensitivity analyses should be performed whenever calculating *NPV*s. For instance, one should always analyse how the *NPV* is affected by a ceteris paribus change of the discount rate applied. Especially for projects like forest plantations that yield main net benefits particularly late in the future, the *NPV* strongly declines with an increasing discount rate.

The **discounted payback period** (year k in Eq. (16.3)) is the first period at which the summed up discounted net benefits of an investment are greater or equal than zero, so that

$$NPV_{k-1} = \sum_{t=0}^{k-1} (B_t - C_t)(1+r)^{-t} < 0 \ \textit{and}$$
$$NPV_k = \sum_{t=0}^{k} (B_t - C_t)(1+r)^{-t} \geq 0. \tag{16.3}$$

As long as future prices and costs contained in net benefits $NB_t = B_t$—C_t have been calculated with today's prices (i.e. not accounting for inflation), a real interest rate r (i.e. an interest rate adjusted for inflation) should be used when calculating the *NPV*. In the case of future net benefits already accounting for price increases due to inflation, the discount rate applied should be a nominal interest rate (i.e. the interest rate actually paid or received). For a given nominal interest rate rn and a given inflation rate in the real interest rate r is

$$r = \frac{rn - in}{1 + in}. \tag{16.4}$$

For instance, a nominal interest rate rn = 4% and an inflation rate in = 2% yields a real interest rate

r = (0.04–0.02)/(1 + 0.02) = 0.0196 = 1.96%.

Hence, for a relatively small inflation rate in one can say that the real interest rate r approxi-

mately corresponds to the nominal interest rate *rn* minus the inflation rate *in*.

If an *NPV* is greater than zero, in principle, the corresponding project is worthwhile. If there are two alternative projects with identical capital needs (or in the case of plantations with identical needs of land), the project yielding the higher *NPV* is to be preferred. However, as the *NPV* depends on the amount of capital invested, in case of projects that require different amounts of capital, one should also examine the internal rates of return of the different investment alternatives. The **internal rate of return *IRR*** is the **discount rate that**—for given net benefits (B_t—C_t)—**leads to an *NPV* of zero**:

$$NPV = 0 = \sum_{t=0}^{T} (B_t - C_t)(1+IRR)^{-t}. \quad (16.5)$$

When calculating the *IRR* this way, the implicit assumption is made that all positive net benefits (cash-flows) obtained at the end of the different time periods $t < T$ can be reinvested at the corresponding *IRR*. For huge *IRR*s, however, this assumption is unrealistic. In such cases, a **modified *IRR* (*MIRR*)** is to be determined:

$$MIRR = \sqrt[T]{\frac{\sum_0^T NB_t^{pos}(1+rr)^{T-t}}{\sum_0^T NB_t^{neg}(1+rf)^{-t}}} - 1. \quad (16.6)$$

where NB_t^{pos} are all cash flows B_t—C_t that are positive and can be reinvested at a rate of return *rr* and NB_t^{neg} are absolute values of all cash flows B_t—C_t yielding negative amounts of money that need to be financed at an interest rate *rf*.

Constant annual cash-flows in arrear (i.e. a constant yearly rent or an annuity $NB_t = B_t$—C_t = constant = *NB* for all $t = 1, \ldots, T$) can be transformed into one single present value applying the **Present Value Annuity Factor (*PVAF*)**:

$$NPV = \sum_1^T NB(1+r)^{-t} = NB\sum_1^T (1+r)^{-t}$$
$$= NB\frac{(1+r)^T - 1}{r(1+r)^T} = NB \cdot PVAF. \quad (16.7)$$

Thus, the *PVAF* transforms a **constant(!)** yearly payment *NB* (to be obtained for the next *T* years) into one single present value. Be aware that ***t* = 1, …, *T*** and that formula (16.7) applies for payments in arrears. In the case of a **perpetuity** (i.e. an "eternal" annuity $NB_t = NB$ with $t = 1, \ldots, \infty$) the *PVAF* in formula (16.7) can be simplified:

$$NPV_\infty = \sum_1^\infty NB(1+r)^{-t}$$
$$= NB\sum_1^\infty (1+r)^{-t}$$
$$= NB\frac{1}{r} = NB \cdot PVAF_\infty. \quad (16.7a)$$

NPV_∞ is the amount of money that one would have to place today at an interest rate *r* in order to obtain a rent $NB = r\ NPV_\infty$ every year again and again (and for the first time at the end of year 1) without ever depleting the calculated necessary capital stock NPV_∞.

The Reciprocal value of the *PVAF* is the **Capital Recovery Factor (*CRF*)**, which transforms a single present value or payment into *T* constant yearly payments *NB* in arrear (to be obtained after each year *t*; $t = 1, \ldots, T$):

$$CRF = \frac{1}{PVAF} = \frac{r(1+r)^T}{(1+r)^T - 1}. \quad (16.8)$$

The capital recovery factor may also be used to convert the *NPV* of a project or investment into an average yearly profit (i.e. a **profit annuity**) resulting from the corresponding project. For farmers, the notion of a yearly profit is easier to comprehend than the idea of an *NPV* that corresponds to the theoretically obtained amount of money when converting all project-related cash flows into present values and adding them up.

Open Supplementary material 16.1 "Excel spreadsheet Exercise Apple Plantation". This spreadsheet contains realistic cost and benefit assumptions for a German apple plantation. Applying the concepts introduced above when filling in the pink cells, calculate *net present values* and *profit annuities* for different possible useful lifetimes *T* of the plantation. Give its

discounted payback period. For a useful lifetime of $T = 20$ years, also calculate the *internal rate of return*. ◘ Supplementary material 16.2 "Excel spreadsheet Exercise Apple Plantation – Solution" provides a sample solution.

16.1.2 Basic Notions in Case of Continuous Discounting

Discrete discounting, as introduced in the previous section, is a common business practice. However, continuous discounting by means of an interest rate ϱ that is applied continuously (at infinitely small time steps) to a capital stock K_t in order to add compound interest is easier to handle in mathematics than discrete discounting. Continuous capital growth K_t is described by means of Euler's number e (= 2.71828…):

$$K_t = K_0 e^{\rho t} \Rightarrow \frac{dK_t}{dt} = \rho K_0 e^{\rho t} \Rightarrow \frac{dK_t}{dt} = \rho K_t \Rightarrow \frac{\frac{dK_t}{dt}}{K_t} = \frac{\dot{K}}{K_t} = \rho \tag{16.9}$$

The unit of the capital growth rate ϱ is *% divided by the time unit* for which the capital growth function has been calibrated, e.g. *%/year*. Applying the formula for continuous compounding, one can again ask for the present value B_0 of a benefit B_t that will be available in t years:

$$B_t = B_0 e^{\rho t} \Rightarrow B_0 = B_t e^{-\rho t} \tag{16.10}$$

Thus, the term $e^{-\varrho \cdot t}$ **is the discount factor in case of continuous discounting**. Hence, given a discount rate of $\varrho = 2\%$, the present value of an expected benefit of € 100 in $t = 5$ years gives a present value $B_0 = €\ 100\ e^{-0.02 \cdot 5} = €\ 90.48$. So, according to this calculation, 100 Euros in 5 years has the same value as 90.48 Euros today. This is less than the 90.57 Euros found above in the case of discrete discounting according to Eq. (16.1) at a discount rate of 2%. The reason for this discrepancy is that one needs a bit less money today in order to have 100 Euros in 5 years when compound interest (i.e. the interest on the interest) is calculated and added continuously. Every discount rate r (for discrete discounting) can be transformed into an equivalent discount rate ϱ (for continuous discounting):

$$B_0 = B_T (1+r)^{-T} = B_T e^{-\rho T} \Rightarrow \rho = \ln(1+r). \tag{16.11}$$

So, in the case of $r = 2\%$ the equivalent rate $\varrho = \ln(1 + 0.02) = 0.01980 = 1.98\%$ and for the example then $B_0 = €\ 100\ e^{-0.0198 \cdot 5} = €\ 90.57$. In the case of continuous discounting, a real interest rate ϱ corresponds exactly to the difference between the nominal interest rate and the inflation rate (ϱn—in). When all cash flows B_t—C_t occur in arrears always at the end of year t ($t = 1, \ldots, T$), we can write:

$$NPV = \sum_{t=0}^{T} (B_t - C_t) e^{-\rho t}. \tag{16.12}$$

For constant net benefits in arrear $NB_t = B_t$—$C_t = NB$ ($t = 1, \ldots, T$) we obtain:

$$\begin{aligned} NPV &= NB_0 + \sum_{t=1}^{T} NB\, e^{-\rho t} \\ &= NB_0 + NB \sum_{t=1}^{T} e^{-\rho t} \\ &= NB_0 + NB \frac{e^{\rho T} - 1}{\left(e^{\rho} - 1\right) e^{\rho T}} \\ &= NB_0 + NB \cdot PVAF \end{aligned} \tag{16.13}$$

In the case of a *perpetuity* (i.e. an "eternal" annuity $NB_t = NB$ with $t = 1, \ldots, \infty$) the **continuous discounting Present Value Annuity Factor (*PVAF*)** simplifies to $PVAF = 1/(e^{\varrho} - 1)$. Again, the Capital Recovery Factor (*CRF*) transforming a single present payment into T yearly payments (always to be obtained at the end of year t; $t = 1, \ldots, T$) is given by the reciprocal value of the *PVAF*:

$$CRF = \frac{1}{PVAF} = \frac{\left(e^{\rho} - 1\right) e^{\rho T}}{e^{\rho T} - 1}. \tag{16.14}$$

In the special case of a **constant flow of money throughout the whole year *NBfl*** (i.e. a constant yearly amount NB_{fl} being equally dis-

tributed over the year t, $t = 1, \ldots, T$) the money obtained at every time span Δt amounts to $NB_{fl} \cdot \Delta t$. Assuming infinitely small time steps $\Delta t = dt$, discounting and summing up these payments yields:

$$NPV = \int_0^T NB_{fl}\, e^{-\rho t}\, dt = NB_{fl} \int_0^T e^{-\rho t}\, dt$$
$$= \frac{1 - e^{-\rho T}}{\rho} NB_{fl} = PVAF \cdot NB_{fl}. \quad (16.15)$$

For T approaching infinity–analogously to the case of discrete discounting (see Eq. (16.7a))– the PVAF collapses to $1/\varrho$.

16.1.3 Calculating Average Cost Covering Prices for (Bio-) Energy

When comparing different ways to produce energy, the average cost per unit (e.g. of electricity expressed as Euro per kWh) needs to be correctly calculated. In principle, this average cost corresponds to a hypothetical **cost covering electricity price** ($P_t = P$) in Euro per kilowatt-hour (€/kWh) that is assumed to be constant over the years t. The International Energy Agency (IEA) calls this cost covering electricity price **Levelised Costs of Electricity** (*LCOE*). To fully cover all costs, the present value of all benefits needs to be equivalent to the present value of all costs (general representation):

$$\sum_{t=0}^{T} P \cdot E_t \left(1+r\right)^{-t} + \sum_{t=0}^{T} H_t \left(1+r\right)^{-t}$$
$$= \sum_{t=0}^{T} \left(I_t + M_t + F_t + C_t + D_t\right)\left(1+r\right)^{-t}$$

$$\Rightarrow LCOE = P$$
$$= \frac{\sum_{t=0}^{T} \left(I_t + M_t + F_t + C_t + D_t - H_t\right)\left(1+r\right)^{-t}}{E_0 + \sum_{t=1}^{T} E_t \left(1+r\right)^{-t}} \quad (16.16)$$

with I_t = Investment expenditures in year t; M_t = Operations and maintenance expenditures in year t; F_t = Fuel expenditures (if relevant) in year t; C_t = Carbon costs in year t (if relevant); D_t = Decommissioning cost in year t; H_t = Value of heat produced in year t (if relevant); r = real discount rate (here: discrete discounting, for continuous discounting the discount factors $(1 + r)^{-t}$ are to be replaced by $e^{-\rho \cdot t}$); E_t = Electricity generation in kWh in year t and $P = LCOE$ = Levelised Costs of Electricity in €/kWh. Given that $E_0 = 0$ (i.e. no electricity being produced when the power plant is under construction) and that for $t = 1$ through T the yearly energy production $E_t = E$ is constant we can write:

$$P = \frac{\sum_{t=0}^{T} \left(I_t + M_t + F_t + C_t + D_t - H_t\right)\left(1+r\right)^{-t}}{E \sum_{t=1}^{T} \left(1+r\right)^{-t}}$$

$$= \frac{\sum_{t=0}^{T} \left(I_t + M_t + F_t + C_t + D_t - H_t\right)\left(1+r\right)^{-t}}{E \cdot PVAF}. \quad (16.16a)$$

Considering that expenditures I_t occur only at the beginning and costs D_t at the end of corresponding projects, one may discuss how an increasing discount rate r applied by decision makers affects the average cost calculation according to Eq. (16.16) with respect to the costs components I_t and D_t. An interesting application and comparison of LCOE for different renewable energy technologies is given in Kost et al. (2021).

16.1.4 Cost–Benefit Analysis and Environmental Externalities

Externalities related to natural and environmental resource use result mainly from regulating and cultural ecosystem services. Social losses due to resource degradation that is linked to certain production activities need to be accounted for when providing for thorough bio-economic cost–benefit analyses or cost calculations. The monetary valuation of corresponding externalities is beyond the scope of this chapter. Here, in the context of investment appraisal, we just want to ask how to find an adequate discount rate that should be applied when dealing with environmental benefits (or possible benefits foregone) that occur partly far away in the future. Many resource use decisions, especially when leading to depletion or ecosystem degradation, have a long-term

impact. Hence, when discounting future environmental benefits, two questions arise: (1) Should common economic net benefits be discounted the same way as the value of ecosystem services that are linked to nature preservation?—(2) Which discount rate should be chosen when dealing with very long time horizons exceeding our own lifetime?

(1) To find an answer to the first question the ideas put forward by Krutilla and Fisher (1975) may be useful: Let $B(D)_t$ be the annual benefit (e.g. farm produce) valued at today's market prices arising in year t from the development of some pristine land (e.g. forestland or moor) that is converted to farmland in year $t = 0$. $C(D)_t$ is the corresponding annual cost, incurred when purchasing all inputs necessary to maintain production. Also, these costs are valued at present market prices. In contrast, $B(P)_t$ is the social benefit resulting from the ecosystem services provided by the pristine land. These annual environmental benefits will be forgone once the land will have been converted. They may be referred to as benefits of "wilderness" preservation. Also, these yearly benefits–which become opportunity costs once the land has been converted—are assessed based on today's price and income conditions. ϱ is a real discount rate for continuous discounting. (N.B.: inflation does not matter in this context as it is simply a general price increase.) Then the NPV of the development project is:

$$NPV = \int_0^T \left\{B(D)_t - C(D)_t\right\} e^{-\rho t} dt - \int_0^T B(P)_t\, e^{-\rho t} dt \qquad (16.17)$$

The second integral is the overall environmental cost of the development project in terms of "wilderness" benefits foregone. The interesting question now is how the values $B(D)_t$, $C(D)_t$ and $B(P)_t$ will evolve over time relative to each other. In this context, Krutilla and Fisher (1975) believe that the relative value of annual benefits from "wilderness" preservation $B(P)_t$ is likely to increase over time when compared to the prices contained in $B(D)_t$ and $C(D)_t$. The reasons are (*i*) the prospects of ongoing economic growth and technical progress that will reduce the relative value of the net benefits $B(D)_t$—$C(D)_t$ that result from the development of the pristine land, (*ii*) supposed high income elasticities of demand for certain ecosystem services from "wilderness" in contrast to stagnating (or even decreasing) supply of such services and (*iii*) lacking substitution possibilities regarding these ecosystem services. Assuming that the value of annual benefits from "wilderness" preservation is given by $B(P)_t = BP_0\, e^{\alpha t}$ with BP_0 being its present value and α the rate at which this value grows over time we can write:

$$NPV = \int_0^T \left\{B(D)_t - C(D)_t\right\} e^{-\rho t} dt - \int_0^T BP_0\, e^{\alpha t}\, e^{-\rho t} dt. \qquad (16.18)$$

Further assuming that the annual benefit BP_0 is equally distributed over the year and that the "wilderness" benefits could be enjoyed for an infinite number of years ($T \to \infty$) in case the pristine land was preserved, applying Eq. (16.15) yields:

$$NPV = \int_0^T \left\{B(D)_t - C(D)_t\right\} e^{-\rho t} dt - BP_0 \int_0^\infty e^{-(\rho-\alpha)t} dt = \int_0^T \left\{B(D)_t - C(D)_t\right\} e^{-\rho t} dt - \frac{BP_0}{\rho - \alpha}. \qquad (16.19)$$

Hence, the larger the assumed growth rate α (i.e. the future relative value increase of ecosystem services emanating from pristine land), the less likely it is that the project should go ahead. When the rate α is close to or even equals the discount rate ϱ, the development project should not be implemented (as then $BP_0/(\varrho - \alpha) \to \infty$). One should be aware that in practice, no matter what the assumed values of $B(D)_t$, $C(D)_t$ and $B(P)_t$ are, the project decision finally made by policy makers strongly depends on their individual discount rates as well as on their assumptions on how the scarcity of "wilderness" related ecosystem services will increase in the future.

(2) Applying a high discount rate in cost–benefit analysis when future environmental benefits are at stake means that these benefits receive a particularly low weight (the lower the farer away in the future they occur). When

increasing the discount rate applied the NPV of a development project that contains environmental costs as future benefits forgone then is more prone to become positive at least as long as the initial investment cost is relatively small, and especially when the useful life of the project is much shorter than the expected time span during which the corresponding environmental impacts are relevant. One may think about nuclear energy and its very long-lasting environmental impact in this context. Discounting future generations' benefits foregone entailed by today's resource use means systematically diminishing the opportunity costs inflicted on people living in the future. It is an ethical issue of whether this is acceptable or not. It is frequently argued that the **social discount rate**, applied by a benevolent government explicitly accounting for the welfare of future generations, should be lower than common **private discount rate**s, applied by private decision makers, who are planning for their own business and usually deal with time horizons covered by their expected lifetimes. However, there may also be reasons to use relatively high social discount rates in project appraisal: firstly, this is not always unfavourable for the environment, as a high discount rate means not only according low weight to environmental damages in the far future but also lower weight to project benefits in the medium term (this aspect is the more relevant the higher the initial investment cost). Secondly, applying relatively high discount rates is justified when believing that because of economic growth future generations will be wealthier than our generation and able to substitute the lost environmental benefits in question. After all, the answer to the question which discount rate to use then partly depends on how optimistic about future technical progress and resource substitution possibilities we are. When no substitute for an essential ecosystem service is in sight a low discount rate is to be chosen as suggested by Krutilla and Fisher (1975). Following ideas expressed by Weitzmann (1998), the discount rate applied may also depend on the time horizon t itself:

$$NPV = \int_0^T \left\{ B(D)_t - C(D)_t - B(P)_t \right\} e^{-\rho_t t} dt$$
$$\text{with } \rho_t = \rho(t) \text{ and } \frac{d\rho}{dt} \leq 0. \tag{16.20}$$

This involves using higher discount rates (derived from common market interest rates) for the near future. For the remote future, lower discount rates should be applied. This last point is all the more relevant as one does not believe in the ongoing future growth of wealth.

16.2 Biological Growth Functions

When trying to optimise the use of a renewable resource, one needs to describe the development of the corresponding resource stock over time. Often it is adequate to describe biological growth as a function of current stock volume S_t. Defining

$$\frac{dS_t}{dt} = S'(t) = \dot{S} = \text{rate of change},$$
$$g(S_t) = \frac{\frac{dS_t}{dt}}{S_t} = \frac{\dot{S}}{S_t} = \text{growth rate of the stock}, \quad \text{then}$$

$G(S_t) = g(S_t) \cdot S_t$ is the biological growth function or regeneration function that gives for every stock size S_t the related net biological growth $G(S_t)$. In the simplest case, when the rate of change dS_t/dt is proportionate to the current stock (meaning that $g(S_t) = g$ is a constant), we have exponential growth (see the dotted graph and the corresponding differential equation in ◘ Fig. 16.1).

However, an undisturbed evolution of the wood volume of a plantation is more likely to correspond to the simple logistic growth displayed in ◘ Fig. 16.1. For small stock sizes S_t the value of the bracket in the differential equation for logistic growth is close to 1. Thus, at the beginning, there will be exponential growth; then, the growth rate of the stock will continuously decline until the stock volume asymptotically approaches an upper bound. The quadratic growth function or regeneration function $G(S_t)$ leading to logistic growth is said to be density dependent (the growth depending on plant or population density). $G(S_t)$ is a differential equa-

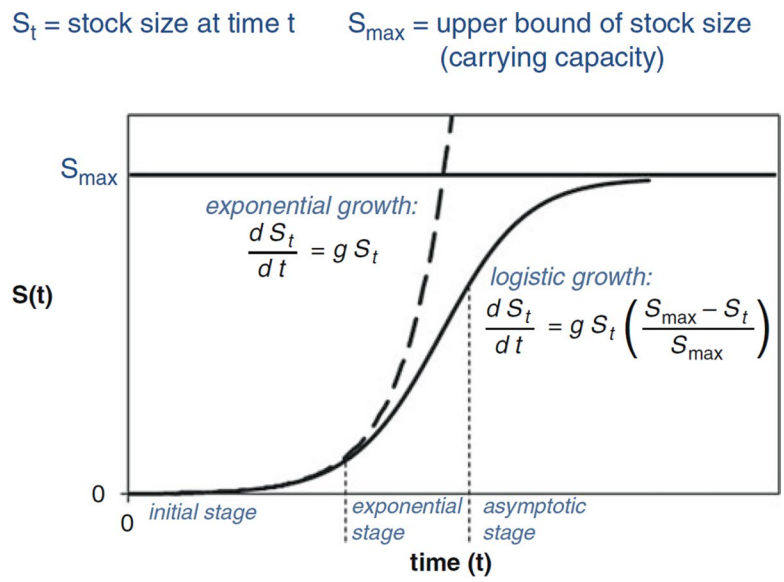


Fig. 16.1 Stock size over time for exponential growth and for logistic growth

tion as the derivative of S_t is a function of S_t itself:

$$G(S_t) = \frac{dS_t}{dt} = gS_t\left(\frac{S_{\max} - S_t}{S_{\max}}\right) = gS_t - \frac{gS_t^2}{S_{\max}} \quad (16.21)$$

Solving Eq. (16.21) for S_t yields the development of the stock volume over time for an initial stock size S_0:

$$S_t = \frac{S_{\max}}{1 - \left(\frac{S_0 - S_{\max}}{S_0}\right)e^{-gt}}. \quad (16.22)$$

For convenience, when modelling the growth of a plantation for a certain co-domain of time, function (16.22) may be approximated relying upon a cubic function $S_t = a*t + b*t^2 + c*t^3$ (a and b being positive parameters, c being a negative parameter).

However, there may be additional (e.g. harvest related) factors influencing dS_t/dt in every time period that further complicate the growth function and the resulting equation describing the stock volume over time S_t. In such cases and when there is a clear functional relationship between $dS_t/dt = S'(t)$ and S_t, we may rely upon the **Euler method** (according to *Leonhard Euler*, 1707–1783) to model stock development over time. This method is a numerical procedure to approximately solve differential equations for which an initial value is known. Its basic principle is to calculate stock size $S(t_{k+1})$ at point in time t_{k+1} ($= t_k + \Delta t$) by simply adding the change (derived from the known function $G(S_t)$) taking place during time period Δt to the stock size $S(t_k)$ at point in time t_k:

$$S(t_{k+1}) = S(t_k + \Delta t) \approx S(t_k) + S'(t_k)\Delta t. \quad (16.23)$$

If this procedure is repeated again and again, one obtains an approximation for the development of the stock volume $S(t_k)$ at consecutive points in time t_k with $k = 0, \ldots, T\text{-}1$). The resulting time path $S(t)$ will be more accurate the smaller the chosen time step Δt.

16.3 Forest Economics and Bio-Economic Modelling of Plantations

From an Institutional Economics point of view and accounting for different possible institutional settings, natural forests yield different kinds of resources. Forests provide for renewable resources as **private goods**: resource units can be allocated on the margin (i.e. consumed in

small units) and property rights are usually enforceable (e.g. timber in German forests). Other forest-related renewable resources are **common pool resources**: resource units can be allocated on the margin; there is rivalry in consumption, but excludability is only obtained at prohibitively high cost (e.g. mushrooms in German forests). Thus, whether a resource is a private good or a common pool resource depends on the specific distribution of property rights along with local institutions and transaction costs for the enforcement of property rights. In addition, forests yield several **environmental resources as public goods (or forest use related positive externalities)** that cannot be allocated on the margin and whose beneficiaries usually cannot be excluded and do not affect each other's utility (i.e. non-excludability and non-rivalry in consumption) (e.g. many forest-related ecosystem services). Further examples for forest-related private or common pool resources are fuelwood, charcoal, pulpwood, fruits, nuts, mushrooms, medicinal plants, honey, wild game, drinking and irrigation water. Examples for positive externalities are cultural ecosystem services because of a forest's recreational and aesthetic amenities or supporting and regulating ecosystem services like protection against landslides, the provision for plant and animal habitats, soil formation and nutrient cycling, water and air quality regulation, waste decomposition, climate regulation and CO_2-storage. Hence, forests are multi-attribute assets, which should be kept in mind when analysing optimum harvesting strategies. In the following, however, we will focus on wood production as in traditional forest management. Forest land or a forest plantation can be seen as a capital asset with intrinsic growth and often an opportunity cost as the land may be used otherwise. The objective is to maximise the NPV of a forest plantation. First, a single rotation will be considered (i.e. trees are planted and logged at age T, then the land will be used for a non-forest purpose, e.g. for agriculture). Second, optimisation will be performed for an infinite rotation (i.e. after every clear-cutting the same tree species will be replanted). Third, we will briefly discuss how positive forest externalities affect optimum harvest strategies. A more comprehensive analysis of the optimum harvesting strategies presented in this subchapter, along with a detailed example can be found in Perman et al. (2011).

16.3.1 Optimum Resource Use in a Single-Rotation Forest Model

Let kpl be the initial planting costs (at time $t = 0$), P today's price per unit of harvested timber, c the marginal harvest cost–so that $p = P—c$ is the so-called stumpage price (value of a timber unit free of harvest cost)–, R the opportunity cost of the forest land (e.g. agricultural land rent foregone), ϱ the real discount rate (continuous discounting), T the harvest age of the stock (i.e. the time when the plantation is to be clear-cut) and S_T the volume of the stock reached at time T. Thus, the harvest age T is to be chosen in a way that the following NPV is maximised:

$$NPV(T) = -kpl - \int_{t=0}^{T} \mathrm{R} e^{-\rho t} dt + pS_T e^{-\rho T}. \qquad (16.24)$$

As the land's opportunity cost is constant over time and applying Eq. (16.15) we get

$$NPV(T) = -kpl - R\frac{1-e^{-\rho T}}{\rho} + pS_T e^{-\rho T}. \qquad (16.25)$$

Calculating the first derivative of $NPV(T)$ and rearranging the first-order condition $NPV'(T) = 0$, necessary to achieve an optimum, we find:

$$p\frac{dS_T}{dt} = \rho p S_T + R. \qquad (16.26)$$

Consequently, the optimum harvest time T is reached when in the last year of forest use (in period T) the stumpage value of the last period's stock increase ($p\, S_T/dt$ = additional income when waiting one more period) is equal to the interest to be earned when harvesting the whole stock ($\varrho\, p\, S_T$ = additional income when converting attained forest capital into cash) plus the opportunity cost

of the land (R = additional income when using the land alternatively, e.g. for crop production). If the value increment from forest growth on the left-hand side of Eq. (16.26) is still greater than the opportunity cost of tied-up capital and land displayed on the right-hand side, it is still better to wait for the harvest and let the forest grow instead of the capital. One could also say that we compare possible biological growth with economic growth possibilities (a truly "bio-economic" consideration). Slightly rearranging the optimum condition (16.26) yields:

$$\frac{\dot{S}_T}{S_T} = \rho + \frac{R}{pS_T}. \tag{16.27}$$

saying that at optimum harvest time T the growth rate of the stock should be equal to the real interest rate plus the relative capital increase from alternative land use—or: the growth rate of the stock should equal the possible rate of return of the tied-up capital (incl. land). The latter is the possible capital growth rate when converting the forest (the natural capital) into cash.

16.3.2 Optimum Resource Use in an Infinite-Rotation Forest Model

In the case of no alternative land use possibilities (i.e. $R = 0$), it does not really make sense to assume that the forest land will be left fallow after T years. If the forest plantation turned out to be profitable, the plantation should be replaced after clear-cutting in year T. But then, as long as all assumed price and cost parameters do not change, reforestation should be done again and again at points in time T, 2 T, 3 T, …, nT with n approaching infinity. This is the case of an **infinite** (sequence of) **rotation**(s) with T being the **rotation length**. As the NPV of an infinite rotation is the NPV of the first rotation plus the discounted (residual) value of the land after the first clear-cutting—which is nothing else than the NPV of the infinite rotation discounted back to the present in year T—we can write:

$$NPV = -kpl + pS_T e^{-\rho T} + NPV e^{-\rho T}. \tag{16.28}$$

Hence, the NPV of an infinite rotation is the NPV due to the land use of the first T years plus the discounted NPV of the same infinite rotation. This second term accounts for the still infinite sequence of rotations from period T on. Solving Eq. (16.28) for NPV gives:

$$NPV(T) = \frac{pS_T e^{-\rho T} - kpl}{1 - e^{-\rho T}}. \tag{16.29}$$

Taking the same approach, a similar expression can be deduced for the case of discrete discounting:

$$NPV(T) = \frac{pS_T (1+r)^{-T} - kpl}{1 - (1+r)^{-T}}. \tag{16.29a}$$

Generalising, the terms in the numerators of Eqs. (16.29) and (16.29a) stand for the net present value of a single rotation of one investment out of a sequence of infinitely repeated identical investments (see Eqs. (16.35) and (16.36) in ▶ Sect. 16.4, below).

Again, we can use the first-order condition $NPV'(T) = 0$ to derive an optimum condition that needs to be fulfilled at harvest time T (and at times 2 T, 3 T, …, nT as well). This way, from Eq. (16.29) we obtain the so-called **Faustmann rule** (in honour of *Martin Faustmann*, 1822–1876):

$$\frac{p\dfrac{dS_T}{dt}}{pS_T - kpl} = \frac{\rho}{1 - e^{-\rho T}}. \tag{16.30}$$

Solving Eq. (16.29) for kpl and entering the corresponding term for kpl into Eq. (16.30) yields, after rearrangement, a version of the Faustmann rule that is quite similar to condition (16.27) above:

$$\frac{\dot{S}_T}{S_T} = \rho + \frac{\rho NPV}{pS_T}. \tag{16.31}$$

The rotation length T is to be chosen so that when harvesting, the growth rate of the stock just equals the interest rate plus the relative capital increase due to the average land rent from future forest use. Again, the possible growth rate of the stock should be equal to the possible rate

of return of the tied-up capital (incl. land). ϱNPV is the perpetuity (the "eternal" annuity) from continuous forest use. In this context, the NPV is also referred to as "site value" of the forest land (i.e. the maximised NPV from an infinite number of rotations).

16.3.3 Forest Model with Positive Externalities

Finally, it should be discussed how the above-mentioned forest externalities affect wood harvesting strategies. For simplicity, let us assume that these external benefits FE (e.g. from habitat support or landscape amenities) occur after a certain time, once the forest will have been planted and remain constant till clear-cutting at time T. From a social point of view and according to the same reasoning that led to condition (16.27) for the single-rotation forest model, the optimum condition to determine harvest time then is:

$$\frac{\dot{S}_T}{S_T} = \rho + \frac{R - FE}{p\, S_T}. \tag{16.32}$$

Now, the yearly opportunity cost of the land R is diminished by the yearly welfare gains due to forest externalities FE. As the right-hand side of this optimum condition is smaller now than in the case of $FE = 0$, and considering that the growth rate of the stock is declining because of logistic growth, the optimum harvest age T will occur later than when merely considering wood benefits. Unsurprisingly, positive forest externalities will delay clear-cutting and forest replacement by an alternative land use.

The optimum conditions for traditional forest management derived in this chapter should be applied when dealing with certain types of plantations. However, one should be aware that, given the multiple beneficial ecosystem services related to the existence of natural forests (see ▶ Sect. 8.3), clear-cutting of forests should be avoided. According to § 5 (3) of the *German Federal Nature Conservation Act,* forests should be managed sustainably without clear-cutting. "**Selective forestry**" to obtain near-natural forests is to be implemented instead. This allows for continuous wood harvest and natural regeneration. The issue of optimum forest use over time then turns out to be a question of realising **maximum sustainable yield**. In principle, this means the forest manager needs to find the stock volume at which the forest regeneration function $G(S)$ (see Eq. (16.21) as an example) is at its maximum.

16.4 Determining the Optimal Replacement Time in Agriculture and Horticulture

The reasoning applied in ▶ Sect. 16.3 can be easily extended to assets or projects that also involve benefits and costs between time periods 0 and T. (e.g. hop gardens, apple plantations, greenhouses). In addition to the symbols already introduced let ka be the initial investment cost for the asset considered (at time $t = 0$) and Ra_T the residual value (salvage value) of the asset that is received at time T. The NPV of such an investment is:

$$NPV(T) = -ka + \sum_{t=1}^{T} (B_t - C_t - R) e^{-\rho t} + Ra_T e^{-\rho T}. \tag{16.33}$$

The **ex ante optimum useful lifetime** T is obtained again by considering NPV′(T) = 0 leading to

$$B_T = C_T + R - \frac{dRa_T}{dt} + \rho Ra_T. \tag{16.34}$$

This means the optimum lifetime of the investment is reached once the marginal benefit when using the asset one more period (B_T) is equal to the marginal cost of using it one more period. This marginal cost consists in additional operating costs (C_T) plus the opportunity cost of the land needed (R) plus the amount of the loss due to a reduced residual value (dRa_T/dt is usually negative and corresponds to depreciation of the asset) plus the interest forgone because the residual value is cashed one time period later (ϱRa_T).

In the case of identical replacement of the asset, analogously to Eq. (16.29) the *NPV* of an infinite sequence of the corresponding investment is:

$$NPV(T) = \frac{-ka + \sum_{t=1}^{T}(B_t - C_t)e^{-\rho t} + Ra_T\, e^{-\rho T}}{1 - e^{-\rho T}} = \frac{NPV(T)^*}{1 - e^{-\rho T}}. \quad (16.35)$$

NPV(*T*)* being the *NPV* of a single investment. For discrete discounting the corresponding *NPV* is:

$$NPV(T) = \frac{-ka + \sum_{t=1}^{T}(B_t - C_t)(1+r)^{-t} + Ra_T\,(1+r)^{-T}}{1 - (1+r)^{-T}} = \frac{NPV(T)^*}{1 - (1+r)^{-T}}. \quad (16.36)$$

Calculating *NPV*(*T*) by means of formula (16.35) or (16.36) for different possible replacement times *T* and searching for the highest *NPV* leads to the optimum **ex ante replacement time**. *Ex ante* here means that the corresponding plantation is not yet implemented, and one wants to determine the optimum useful life given expected prices and costs before starting the project.

Open Supplementary material 16.1 "Excel spreadsheet Exercise Apple Plantation". By filling in the pink cells and applying Eq. (16.36), for the case of discrete discounting calculate *NPVs* of an infinite sequence of apple plantations assuming different rotation lengths *T* (see Supplementary material 16.2 "Excel spreadsheet Exercise Apple Plantation - Solution" for a solution).

In contrast to the previous analysis, in an **ex post decision situation,** the asset or the plantation is already being used, and one wants to know when to replace it with an alternative or an identical land use. Very important: when making *ex post* decisions on how long to continue the use of an asset, a plantation or a forest stand, the initial investment costs of the *present* use (*kpl* or *ka*) do not matter! Once an investment has been implemented, these initial costs are so-called **sunk costs** already paid for in the past. Such sunk costs cannot be recovered. In ex post decision situations, marginal net benefits of the current land use have to be compared to average net benefits *ANB* of the considered possible future land use. The investment is to be replaced when:

$$B_T - C_T + \frac{dRa_T}{dt} - \rho Ra_T \le ANB. \quad (16.37)$$

As long as the marginal net benefit when continuing to use the old asset (i.e. the left-hand side of Eq. (16.37)) is still greater than the *ANB* of the future use, the current use should be continued. *ANB* is to be determined by calculating a profit annuity for the new (replacing) investment. Be aware that in Eq. (16.37) dRa_T/dt (i.e. the depreciation in period *T*) is usually negative.

Questions

1. Explain the basic difference between discrete and continuous discounting.
2. In which cases can one make use of a *Present Value Annuity Factor (PVAF)* when calculating a *Net Present Value (NPV)* and under which conditions does this factor collapse to "one divided by the discount rate".
3. Explain and illustrate by means of a formula containing the main cost components how to calculate cost covering electricity prices for a biogas plant.
4. Following the ideas of Krutilla and Fisher (1975), for which reasons should the future value of certain ecosystem services (i.e. benefits related to "wilderness" preservation) be discounted at relatively low discount rates in cost benefit analysis?
5. Explain the basic idea of the *Euler method.*
6. Write down and explain the *Net Present Value (NPV) (a) of a single-rotation forest model* and *(b) of an infinite-rotation forest model* – with reference to the growth rate of the stock, for both cases give an optimum condition that is to be met when maximising the NPV.
7. Explain how to identify the *ex ante optimum useful lifetime* of an agricultural asset (e.g. a rubber plantation) *(a)* in the

case of an alternative land use opportunity, *(b)* in the case of identical replacement.

8. Give a rule for the optimum replacement time in an *ex post decision situation* and explain why so-called *sunk costs* do not matter in this context.

Answers

1. In continuous discounting compound interest (i.e. the interest on the interest) is assumed to be calculated and added continuously to the principal sum, whereas in the case of discrete discounting this is assumed to be done always after one year only.
2. The Present Value Annuity Factor (PVAF) is used in NPV calculations when annual cash flows are constant over time. For perpetuities (infinite time horizon), the PVAF simplifies to $1/r$ under discrete discounting.
3. The constant cost-covering price (LCOE) ensures that the present value of all power plant related revenues equals the present value of all required costs:

$$LCOE = \frac{\sum_{t=0}^{T}\left(I_t + M_t + F_t + C_t + D_t - H_t\right)\left(1+r\right)^{-t}}{E \cdot PVAF}$$

where I_t = investment costs, M_t = maintenance cost, F = fuel costs, C_t = carbon costs, D_t = decommissioning costs, H_t = heat value (all at the respective year), E = constant yearly electricity production.

4. *Krutilla* and *Fisher* (1975) argue for lower discount rates when discounting the value of future ecosystem services due to (1) increasing relative value of ecosystem services, (2) high income elasticity of demand for ecosystem services along with decreasing supply, and (3) limited substitution possibilities for such services.
5. The Euler method approximates solutions to differential equations by iteratively estimating future values based on current values and their rates of change: $S(t_{k+1}) \approx S(t_k) + S'(t_k) \cdot \Delta t$.
6. NPV of forest models and growth rate conditions

Single-rotation model:

$$NPV\left(T\right) = -k_{pl} - R \cdot \frac{1 - e^{-\rho T}}{\rho} + p \cdot S_T \cdot e^{-\rho T}$$

Optimum: condition: When harvesting, the growth rate of the stock should equal the possible rate of return of the tied-up capital (incl. land) $\frac{S_T'}{S_T} = \rho + \frac{R}{p \cdot S_T}$

Infinite-rotation model:

$$NPV\left(T\right) = \frac{p \cdot S_T \cdot e^{-\rho T} - k_{pl}}{1 - e^{-\rho T}}$$

Optimum: condition: When harvesting, the growth rate of the stock should equal the possible rate of return of the tied-up capital (incl. land) $\frac{S_T'}{S_T} = \rho + \frac{\rho \cdot NPV}{k \cdot S_T}$

7. **Alternative land use after the end of lifetime:** Optimum lifetime T is reached, when the marginal benefit when using the asset one more period equals the marginal costs of using it for one more period (including operating costs, depreciation, and forgone interest from the asset's value):

$$\mathrm{B_T} = \mathrm{C_T} + \mathrm{R} - \frac{dR_{a_T}}{dt} + \rho \cdot \mathrm{R_{a_T}}$$

Identical replacement after the end of lifetime: Use the "infinite rotation NPV formula" and calculate NPV(T) for different replacement times T to identify the replacement time that yields the highest NPV(T):

$$NPV\left(T\right) = \frac{-k_a + \Sigma_{(t=1)}^{T}\left(B_t - C_t\right) \cdot e^{-\rho t} + R_a \cdot e^{-\rho T}}{1 - e^{-\rho T}}$$

8. Replacement should occur when the marginal net benefit of current use is less than or equal to average net benefit of future use (ANB): $B_T - C_T + \frac{dR_{a_T}}{dt} - \rho \cdot R_{a_T} \leq ANB$. Sunk costs are irrelevant as they cannot be recovered.

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Processing

The fundamental idea behind the bioeconomy is the processing of bio-based resources into a wide range of products in the food, feed, material, and energy sectors. Due to the specific characteristics of bio-based resources, appropriate conversion approaches need to be selected with the desired application in mind. This part of the book describes these conversion approaches and technologies. They include biorefinery approaches, biotechnological and thermochemical conversion processes, food processing techniques, processes for the production of plant-based alternatives to meat and dairy products, processes for the conversion of bio-based side streams into raw materials for the food industry, fibre extraction, and bioenergy production. It describes how these processes can be supported by digital technologies, and how process and product cost assessment can be performed.

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Biomass Use and Biorefineries

Iris Lewandowski and Ricardo Vargas-Carpintero



Fig. 17.0 Biomass use and biorefineries. (© Universität Hohenheim, Max Kovalenko) https://doi.org/10.1007/000-htw)

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Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/978-3-032-09098-0_17. The videos can be accessed individually by clicking the DOI link in the accompanying figure caption or by scanning this link with the SN More Media App.

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The processing procedures and technologies applied for the conversion of biomass depend mainly on the targeted biomass use, e.g. food, feed, materials or energy, and are mainly determined by the origin, components and physical/general characteristics of the biomass. Biorefining is an integrative and multifunctional overall concept that integrates different processes and technologies (upstream, midstream and downstream operations) using biomass as a diverse source of raw materials to generate a spectrum of intermediate or final products for diverse purposes. Biorefineries can be characterised according to the raw materials used, the processing technologies applied, the platforms, the intermediate and final products they provide, and their size. In this section, the practical functioning of biorefineries is illustrated using the examples of a sugar factory and a pulp mill as traditional biorefineries. A grass biorefinery for the production of biocomposite materials is presented as an example of a more recently developed biorefinery concept. Common to all biorefinery technologies is that they make full use of biomass for different products and incorporate the principle of circularity to close material and energy cycles.

Learning Objectives

After studying this chapter, you will…

- …be able to explain the determinants of biomass uses and processing (see ► Sect. 17.1).
- …be able to describe the principles of the biorefinery concept (see ► Sect. 17.2).
- …be able to classify biorefinery approaches (see ► Sect. 17.2).
- …be able to explain how circularity is realised in biorefineries (see ► Sects. 17.2.1, 17.2.2, and 17.2.3).
- …be able to explain the sustainable processing of biomass into a spectrum of marketable products (chemicals and materials) and energy (fuels, power and heat) (see ► Sects. 17.2.1, 17.2.2, and 17.2.3).

17.1 Determining Biomass Uses

The processing procedures and technologies applied for the conversion of biomass depend mainly on the targeted biomass use, e.g. food, feed, materials or energy. In today's bioeconomy, the decision on the use of biomass is guided by the bio-based economy's value pyramid, which considers the volume requirements in relation to the value of the biomass application (Fig. 17.1).

The value pyramid approach aims to optimise the value of biomass use. In this context, the value of the biomass is determined by its application. It shows that the energetic use of biomass has the lowest economic value and requires large volumes for its production, whilst pharmaceuticals and fine chemicals have the highest value and require comparatively smaller amounts of biomass for their production. To achieve the highest possible value, it can be beneficial to refine the biomass, with each component having its own application and economic value. A biorefinery approach that focuses on optimal value utilisation starts by isolating those substances or materials with a higher value, followed by lower-value uses. However, this concept of focusing on the economic value of individual compounds neglects possible contributions to circularity, sustainable resource use and, in particular, food security. As a result, 'high value' is mainly determined by the economic, rather than the 'need' value. The frameworks of human needs (Muscat et al. 2021) give the highest priority to food production.

How biomass is utilised depends on its origin, characteristics, components and properties (Fig. 17.2). Plant biomass can be sourced from dedicated feedstocks (e.g. sugar crops, starch crops, lignocellulosic crops, oil crops, grasses, aquaculture and marine biomass) or from residual biomass (Cherubini et al. 2009; Aristizábal-Marulanda and Cardona Alzate 2019). The origin determines the potential use of biomass: for example, if it has been classified as waste, its use as food or feed may be restricted by law. Various characteristics determine how biomass can be used

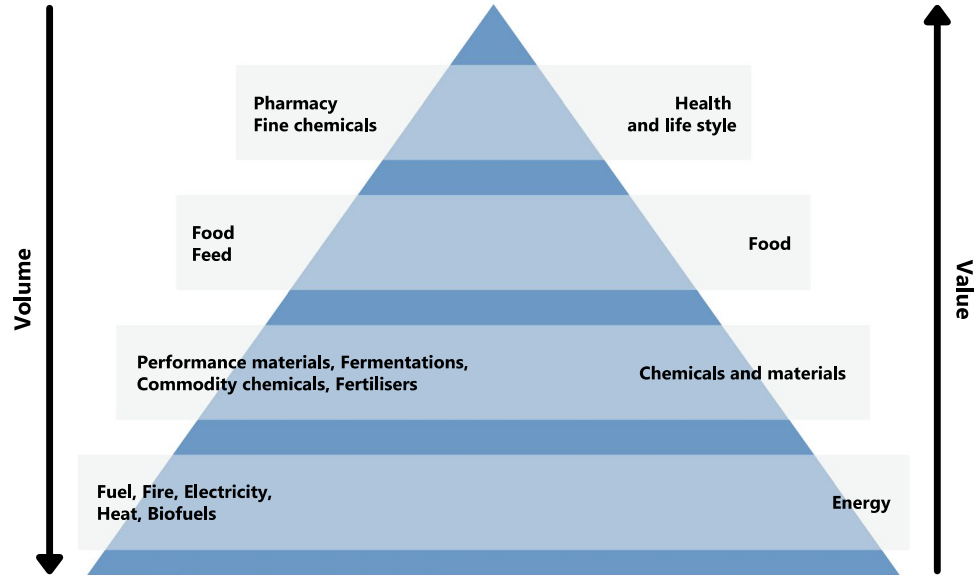


Fig. 17.1 Bio-based economy value pyramid

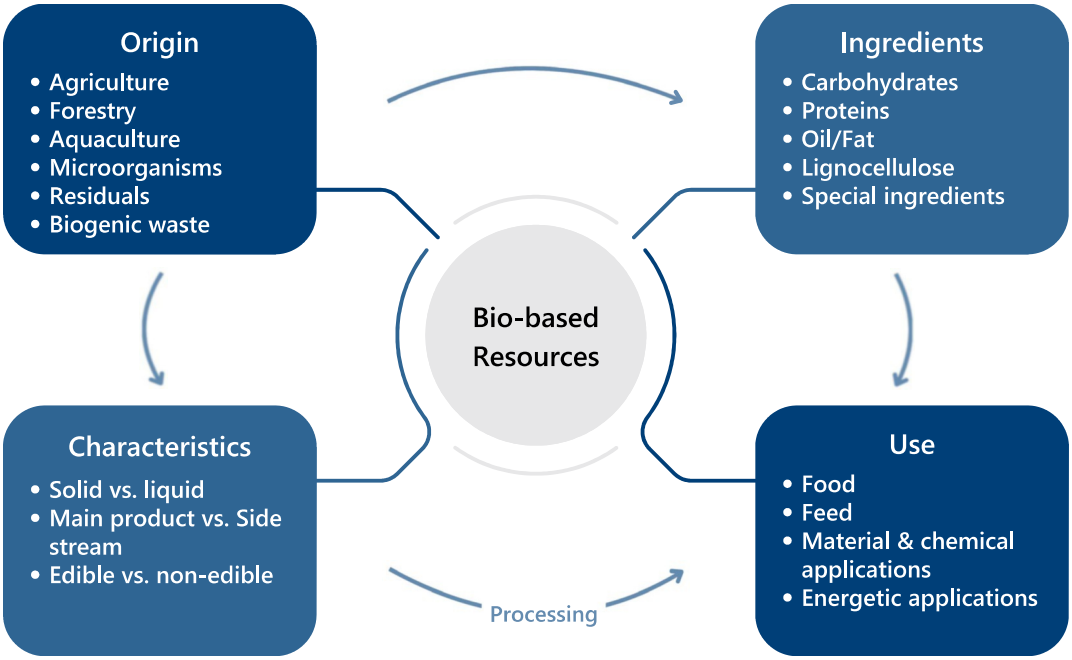


Fig. 17.2 Determinants for the use of bio-based resources, including origin, components and physical/general characteristics

or, from an ethical point of view, should be used, e.g. whether it is edible and should therefore be preferentially used for food applications. The physical conditions of the biomass, in particular whether it is solid and dry or liquid and watery, determine its storability and transportability, but also which processes are suitable for its processing. For example, most carbonisation processes require dry biomass, whereas hydrothermal carbonisation (see ▶ Chap. 19) can also use moist feedstock.

A systematic description of biomass use usually starts with the main components, which are carbohydrates, proteins, oils & fats and lignocellulose, but can also be specific compounds. ◘ Table 17.1 gives examples of typical bio-based products that can be derived from these components.

Biomass generally contains a variety of components (see ▶ Sects. 5.2 and ▶ 12.1). Depending on the degree of processing and the targeted product, some types of biomass undergo only a few industrial conversion steps. For example, in oil mills, rapeseed oil is obtained by pressing as the main process. The remaining press cake, which is rich in protein, can be used as animal feed. However, to increase the value and make full use of all biomass components, a biorefinery approach should be applied. In this way, multiple valorisation routes and processing technologies can be integrated. This approach can be seen as an upgrade strategy for stand-alone agro-industrial processing into more robust and integrated biorefineries (Cardona Alzate et al. 2019).

◘ **Table 17.1** Examples of bio-based products produced from specific biomass components

Component / Use	Oil	Sugar	Starch	Cellulose	Lignocellulose	Specific compounds
Food	Food oil	Food sugar	Food starch	Fibre (supports digestion, but no nutritional value for humans)		Herbs, nutraceuticals, bioactive compounds and natural ingredients
Feed			Grains for pigs and poultry	Feed for ruminants	Roughage, e.g. for ruminants	Feed additives, e.g. pharmaceuticals, vitamins
Material	Colourings, lubricants	Bio-based plastics	Bio-based plastics, coatings	Paper	Building materials	Dyes, pharmaceuticals, cosmetics
Energetic	Biodiesel	1st generation ethanol	1st generation ethanol	2nd generation ethanol	Combustion for heat & electricity	

17.2 Biorefineries

According to the International Energy Agency (EIA) Bioenergy Task 42 (2009) and to VDI (2014), biorefining is defined as an integrative concept for the sustainable processing of bio-based resources (i.e. biomass) into a spectrum of marketable and value-added products, including chemicals, materials, fuels and energy, operated with the aim of full utilisation of the biomass. Biorefineries integrate a set of operations encompassing upstream, midstream and downstream processing. This enables the cascading use of biomass (see ► Sect. 3.3), a higher resource efficiency and integrated energy production (Cardona Alzate et al. 2019). In practical terms, a biorefinery can be an industrial cluster, a facility or an integrated process (Cardona Alzate et al. 2019). Biorefineries are described as multi-product systems with a configuration flexibility that allows the processing of different feedstocks. The choice of products depends on the availability and composition of the biomass, available technologies, processing capacity and conditions, market demand, product functionality, economic viability, and sustainable performance (Aristizábal-Marulanda and Cardona Alzate 2019; Vargas-Carpintero 2024). Biorefineries can be characterised according to (Cardona Alzate et al. 2019):

- The raw materials used (primary or secondary biomass, biomass from arable and green areas, woody biomass, aquatic biomass, biogenic residues).
- The technical processes applied (mechanical-physical, biochemical, chemical, thermochemical (see ► Chap. 19), biotechnological (see ► Chap. 18))
- The platforms and intermediate products produced (e.g. synthesis gas, lignin, hemicellulose, cellulose, starch, oil, protein)
- The products provided (chemicals, materials, food, feed, energy)
- Size (small-scale rural biorefineries, large and very large production facilities)

Figure 17.3 shows the systematic classification approach for biorefineries initially proposed by Cherubini et al. (2009) and further elaborated by VDI (2014) based on the Biorefinery Roadmap for Germany (Bundesregierung der Bundesrepublik Deutschland 2012):

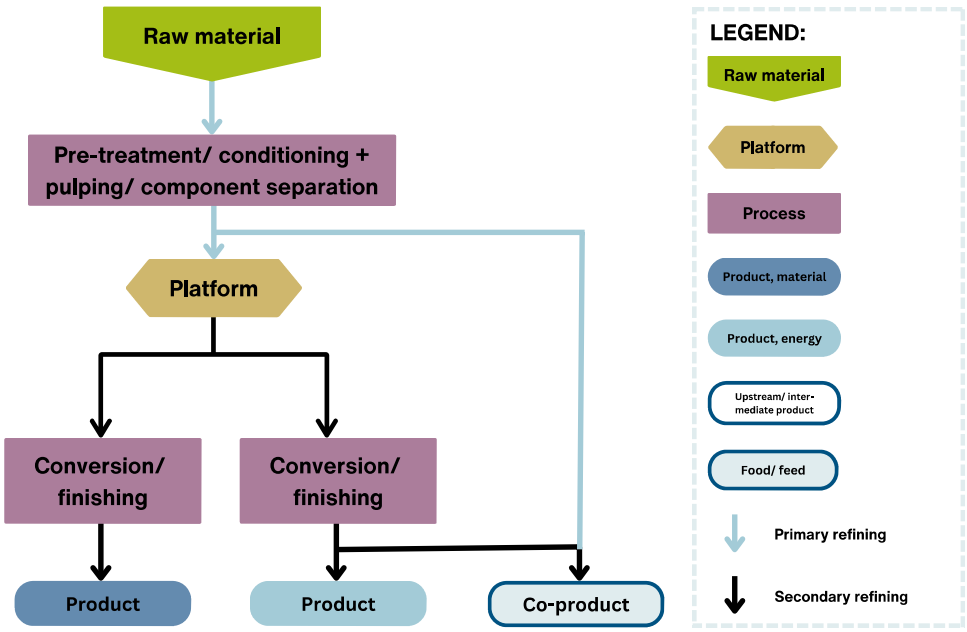


Fig. 17.3 Principles of the biorefinery classification system with related elements (Based on Cherubini et al. 2009 and VDI 2014)

While the broader definition of biorefineries given above does not include food applications, the product classification of biorefineries does (VDI 2014; Cardona Alzate et al. 2019). According to the VDI (2014) extended definition, biorefineries are explicitly integrative and multifunctional overall concepts that integrate various processes and technologies that use biomass as a diverse source of raw materials for the generation of a spectrum of different intermediates and products, whereby food and feed can also arise as co-products. It should be noted, however, that the first biorefinery concepts were applied to the development of food and beverage production, e.g. in breweries and the corn wet-milling industry (Cardona Alzate et al. 2019).

Among the approximately 300 biorefineries in Europe (European Commission 2021), there are several that produce one main bio-based product (1-platform biorefineries), e.g. sugar, starch or oil (Fig. 17.4). However, they all generate by-products that are used as animal feed, fertiliser or for other purposes. This is illustrated below using the example of the sugar factory. Together with pulp and paper mills (not included in the EU biorefinery map shown below), these 1-platform biorefineries are considered traditional biorefineries. More recently developed biorefineries include those that use grass for vari-

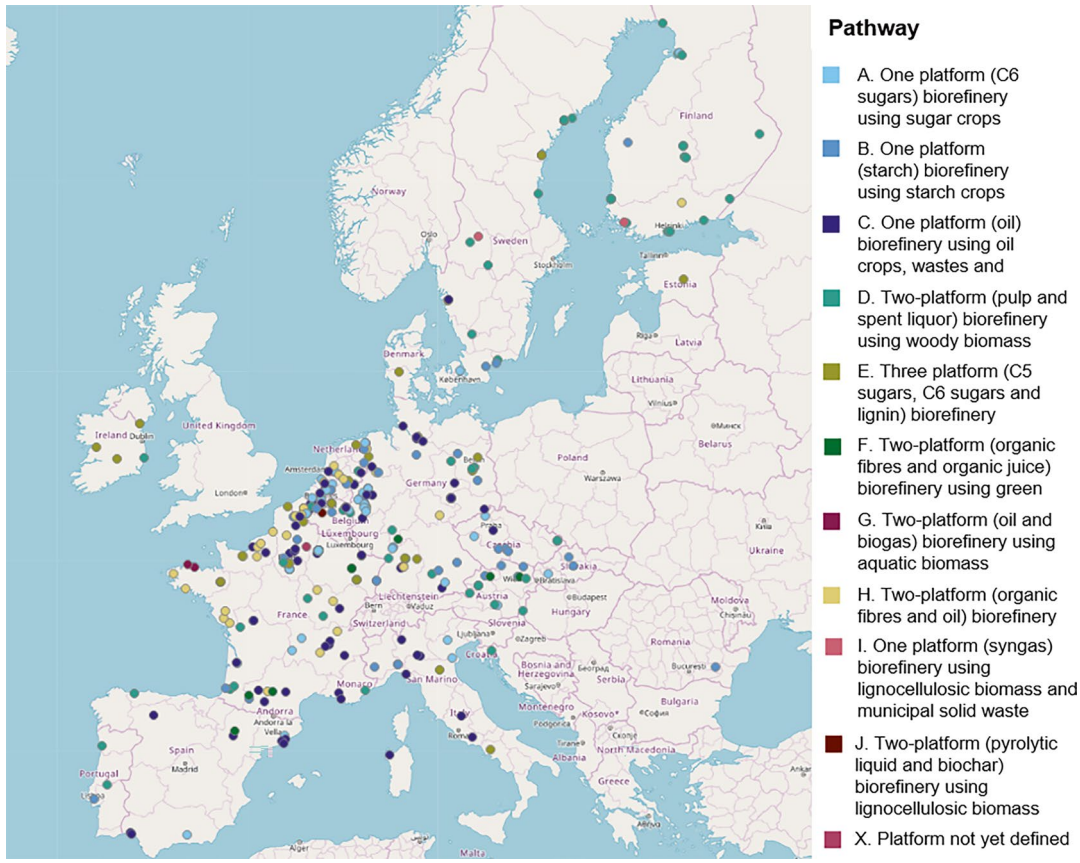


Fig. 17.4 Biorefineries in the EU, derived from the European Commission's ► Data-Modelling platform of resource economics. (From Baldoni et al. (2021), licensed under CC-BY 4.0))

ous purposes. Below we describe a sugar factory and a pulp and paper mill as examples of traditional biorefineries, and a grass biorefinery as an example of a modern biorefinery.

17.2.1 Sugar Factory

The sugar biorefinery (Fig. 17.5) of the company ► Südzucker, located at Zeitz in Germany, is described here as an example, since it is the company's newest plant and combines sugar and ethanol production.

The sugar production process includes the following steps (see Fig. 17.6):

1. *Cleaning and chopping*
   First, the sugar beets are cleaned of soil by washing. The soil is returned to the fields. The cleaned beets are sliced into pieces 3–4 cm long and 2–3 mm thick.
2. *Production of raw juice*
   A conveyor belt transports the beet slices to 20-m-high extraction towers. In a process known as 'countercurrent extraction', they move from the bottom to the top, while 70 °C-hot water flows in the opposite direction. The heat from the water causes the cell walls of the beet chips to open, and the sugar molecules they contain are released into the water. The resulting 'raw juice' (13–15% sugar content) is pumped out at the bottom of the extraction tower. The de-sugared beet pulp is also used, for example, as cattle feed.
3. *Processing of raw juice into thin juice*
   In addition to sugar, the raw juice also contains various organic and inorganic components. These non-sugar substances are bound and excreted with the help of lime and carbon dioxide. What remains is a clear, pale yellow liquid—the thin juice. The remaining lime mixture, carbocalk, is pressed and used as a lime fertiliser in agriculture.
4. *Evaporation and crystallisation*
   In the evaporation station, water is removed from the thin juice in a series of evaporation units until it becomes a thick syrup



Fig. 17.5 Sugar factory of Südzucker AG in Platting, Germany (top) and bioethanol plant in Zeitz, Germany (bottom). (© SimonWaldherr licensed under CC BY-SA 4.0 ► https://creativecommons.org/licenses/by-sa/4.0/ © High Contrast licensed under CC BY 3.0 DE ► https://creativecommons.org/licenses/by/3.0/de/)

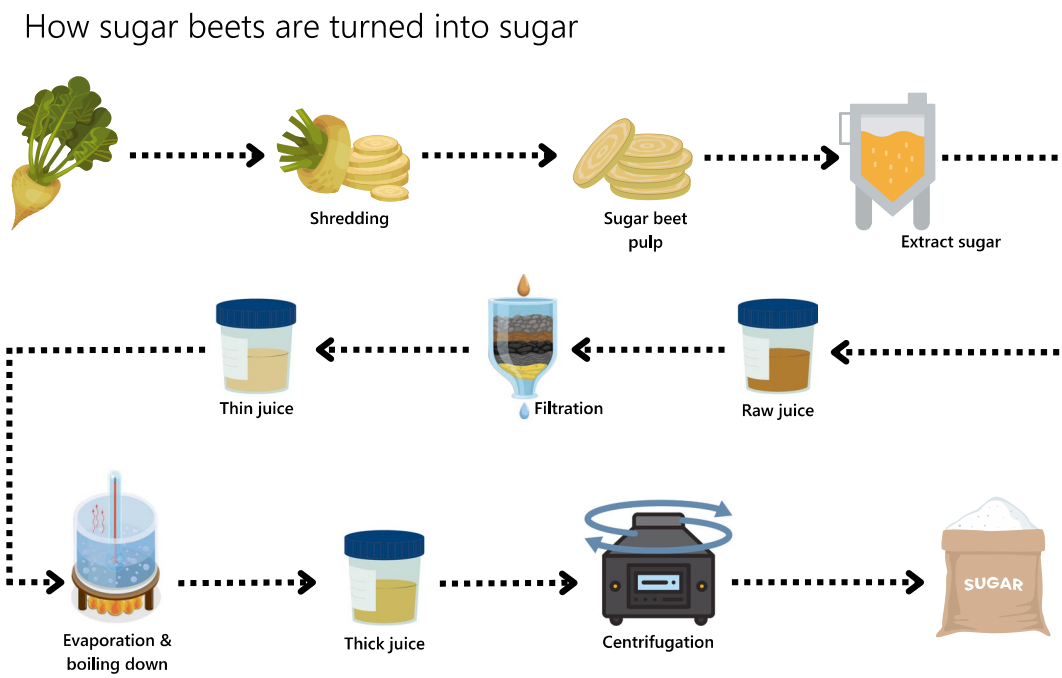


Fig. 17.6 Process of sugar extraction from sugar beets

with a sugar content of 65–70%. The evaporation units are connected to each other in such a way that the steam produced always heats the next stage. This ensures optimal energy utilisation. The resulting thick, golden-brown syrup is further evaporated in the boiling station. This is done under reduced pressure, as the water then evaporates between 65 and 80 °C, and the sugar does not caramelise with this gentle method. At a certain ratio of water to sugar, crystal formation is often stimulated by adding seed crystals in the form of the finest sugar. This creates a thick paste, the so-called filling mass. The crystal mass is poured into mashes to cool. Agitators keep the mass in constant motion, and the sugar crystals continue to grow.

5. *Centrifugation and drying.*
The sugar crystals are separated from the viscous syrup by spinning in high-speed centrifuges. Finally, steam is used to remove the remaining syrup from the sugar crystals, leaving white sugar as the end product. Dissolving this white sugar and allowing it to recrystallise results in a very pure and high-quality refined sugar. The finished sugar is dried, cooled and transported on conveyor belts to large silos. The removed syrup is returned to the boiling station to crystallise. This process is repeated twice in total. The dark brown, viscous syrup that remains after the final crystallisation is called molasses. Molasses still contains around 50% sugar, but this can no longer be crystallised using conventional methods. Molasses is primarily used as animal feed, but also as a raw material in the yeast industry, in alcohol production, in the pharmaceutical industry and in biotechnology.

17

17.2.2 Pulp Mill

For the description of a pulp mill, we have chosen the example of UPM, a Finnish forestry company founded in 1996 (Fig. 17.7). ▶ UPM produces pulp, paper, timber, plywood, labels and composites, bioenergy, biofuels, biochemicals, biocomposites and biomedicals in 11 countries.

The ▶ production processes to produce pulp as a starting material for products such as



Fig. 17.7 UPM pulp mill in Lappeenranta, Finland. (© Tuomas Vitikainen under CC BY-SA 4.0 license ► https://creativecommons.org/licenses/by-sa/4.0/deed.en)

paper, are carried out along the fibre line, the recovery island and the effluent treatment line:

1. *Fibre line*
   In a first step, the wood logs are debarked and chipped. The bark is used for energy production. The wood chips are transported via a conveyor belt to storage and from there to the digester, where the lignin and fibres are separated. For this purpose, the chips are mixed with white liquor, an alkaline solution containing sodium hydroxide and sodium sulphide. The results of the digestion are fibres and black liquor, which consists of dissolved organic material and spent digestion chemicals. This black liquor, which contains half of the wood raw material, is sent on to the recovery island. The digester also produces fibrous pulp, which is brownish in colour due to the residual lignin. To delignify the pulp, it is washed in several steps and then bleached with chlorine dioxide and oxygen-containing chemicals. The washed, screened and bleached pulp is sent to the dryer where it is formed into thick, heavy white sheets that are dried by evaporation steam. The sheets are packed in bales for easy storage and transportation to the customer.
2. *Recovery island*
   This is where process chemicals are recovered from the spent digestion liquor for reuse. Soap is separated from the black liquor and converted into crude tall oil, which can be used to produce biodiesel and bio-naphtha. Black liquor is transformed into a solid substance through evaporation with steam from other process steps. The evaporated water is reused forming a closed loop. Recovered black liquor is burned in the recovery boiler to recover the inorganic chemicals for reuse in the pulping process. The process also generates high-pressure steam for electricity production and low-pressure steam for the various processes in the pulp mill. The energy produced by the pulp mill exceeds its own demands and the excess electricity is fed into the grid. During the re-causticising process of the black

liquor residue, the so-called molten smelt, consisting of sodium carbonate and sodium sulphide, is mixed with weak wash (molten salts from the recovery boiler that are dissolved in process water) to produce green liquor. Mixing this green liquor with burnt lime (quicklime) results in white liquor, which is used for digestion processes in the fibre line.

3. *Effluent treatment line*
   Effluents are treated mechanically and biologically in effluent treatment plants. The resulting biodegradable organic matter can be used for fertiliser production or energy generation.

17.2.3 Grass Biorefinery

Here we describe the company Biowert (https://biowert.com/en/) Industry GmbH, located in Brensbach, Germany, as an operational example of a grass biorefinery. The feedstock is meadow grass supplied by local farmers who cultivate grassland near to the biorefinery.

An annual throughput of about 8000 t of grass is processed in the following steps:

1. *Ensiling of the grass*
   The grass has a water content of 70–75%. It is ensiled in bunker silos to make it storable.
2. *Mechanical treatment of the grass*
   The first processing step in the biorefinery is the mechanical treatment of the grass silage to extract water and isolate grass fibres through pulping, drying and pressing. The water obtained by this process is used within the biorefinery for the pretreatment (slurrying) of the grass silage and covers the entire water demand of the biorefinery processes (Fig. 17.8). The grass fibres are used to produce grass fibre insulation (AgriCell) and natural fibre reinforced plastic (AgriPlast) granules. AgriPlast contains 30–50% grass fibres and 50–70% recycled polyolefin. It can be

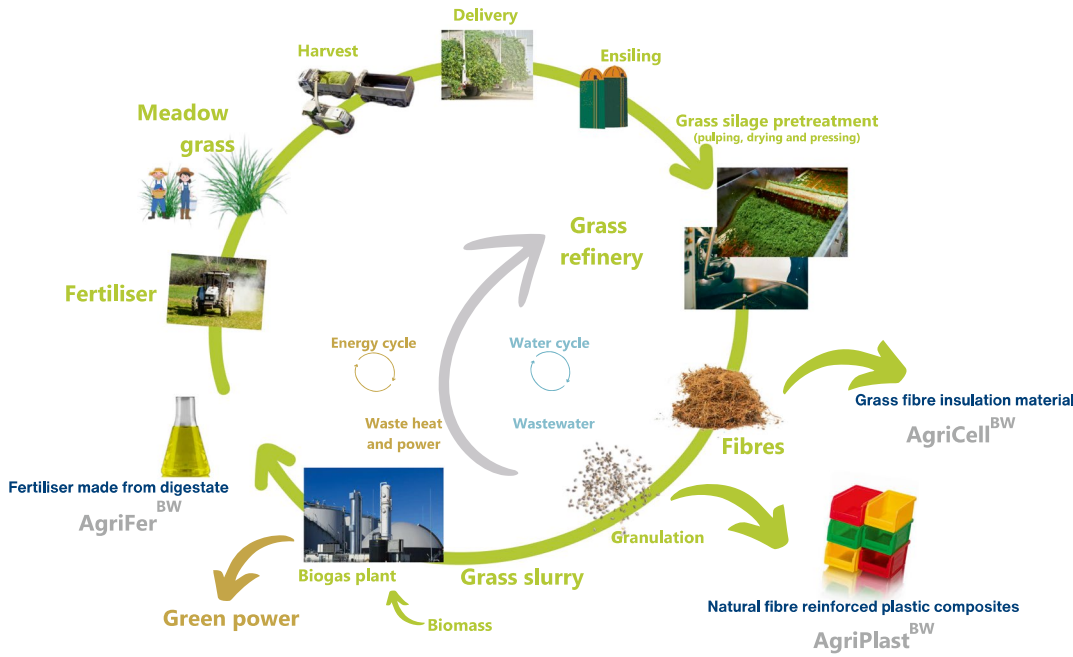


Fig. 17.8 The Biowert grass biorefinery cycle. (Based on IEA Bioenergy 2019)

used for injection moulding for a range of applications and products (Fig. 17.8).

3. *Biogas, heat & power production*
Grass juice remaining from the mechanical pretreatment of grass silage is fed into the biogas plant together with other feedstocks such as food waste and slurry. The heat and electricity produced by the biogas plant are used to meet the energy demand of the biorefinery and excess electricity is exported to the grid.
4. *Fertiliser production from biogas residues*
The digestate from the biogas plant is further processed into a liquid biofertiliser (AgriFer). This is used by local farmers, also for fertilising the meadow grass to be supplied as feedstock to the grass biorefinery (Fig. 17.9).



Fig. 17.9 The grass biorefinery: Refining process (top left), AgriPlast granulates (top right), examples of products made from these (bottom left), and storage and processing of biogas digestates into fertiliser (bottom right). (© Iris Lewandowski)

Questions

1. How are uses and processing of biomass determined?
2. What are the main elements of biorefinery concepts?
3. What is the role of biorefineries in the bioeconomy?

Answers

1. The decision on how to use the biomass can be guided by the value pyramid approach, which aims to optimise the value of biomass use and follows the principle of cascading use of biomass. In this context, the value of the biomass is determined by its application. However, this concept of focusing on the economic value of individual compounds neglects possible contributions to circularity, sustainable resource use and, in particular, food security. As a result, 'high value' is mainly determined by the economic, rather than the 'need' value. The processing procedures and technologies applied for the conversion of biomass depend mainly on the targeted biomass use, e.g. food, feed, materials or energy, and have to be chosen to suit the characteristics, components and properties of the biomass to be processed.
2. Biorefinery concepts explore possible pathways for the refining of biomass as a diverse source of raw materials to generate a spectrum of intermediate or final products for diverse purposes. These generally make use of all biomass components, resulting in various educt streams that can be converted into basic products. Biorefining integrates different processes and technologies, including upstream, midstream and downstream operations. Biorefineries can be characterised according to the raw materials used, the processing technologies applied, the platforms, the intermediate and final products they provide, and their size.
3. Biorefineries are required to make best use of all biomass components and to transform them into high-value products, such as fibres and chemicals. They are an important technology to realise circularity in the bioeconomy. Through biorefining, different material streams are generated and can be directed to the most efficient and ecologically sound use. For example, plant nutrients like nitrogen and phosphorus are recycled from biomass streams and can be brought back as fertiliser to agricultural production.

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Biotechnological Conversion

Karin Moß, Marius Henkel, and Rudolf Hausmann



Fig. 18.0 Biotechnological conversion. (© Uni Hohenheim, Manfred Zentsch) (▶ https://doi.org/10.1007/000-htx)

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This chapter presents key terms and concepts in the field of industrial biotechnology. The inclusion of examples, such as ethanol fermentation and production of polylactic acid (PLA) and propanediol (PDO), allows students to become acquainted with important concepts and their application. Industrial biotechnology, also known as "white biotechnology", is devoted to the exploitation of living cells, such as yeasts, molds, bacteria and enzymes. In the context of a bioeconomy, it may provide methods to replace and complement petroleum-based synthetics. Industrial biotechnology has been identified as a key enabling technology. Nowadays, industrial biochemicals are mainly produced from carbon sources based on sucrose and glucose. In a future bioeconomy, lignocellulosic plant biomass could become a key feedstock. However, for this purpose, technologies are required that can break down lignocellulosic biomass more easily, with less energy input, and creating less waste than is presently the case. The rapid development of genetic, synthetic biology and bioprocessing methods will lead to biotechnology increasingly complementing chemical industries.

Learning Objectives

After studying this chapter, you will…

- …be able to describe the importance of industrial biotechnology for a bio-based economy (see ► Sects. 18.1, 18.2, and 18.5).
- …be able to name and explain the key terms and concepts required to understand basic processes of bioprocess engineering (see ► Sect. 18.3).
- …be able to give examples of biotechnologically derived products of the present and the future (see ► Sect. 18.4).

18.1 Industrial Biotechnology

Industrial biotechnology uses microorganisms and enzymes for the production of bio-based materials. These materials are utilized in the chemical, food and feed, healthcare and biofuels sectors. Currently, biotechnology is a niche within the chemical industry, mostly providing products with demanding structure or stereochemistry requirements.

Historically, biotechnology dealt with uncontrolled food processing, such as in the production of wine, beer, vinegar, bread, cheese and other fermented foods. In 1873, Louis Pasteur received a patent on isolated yeast, and since then the role of yeast in beer brewing and that of bacteria in vinegar fermentation has been exploited, and knowledge-based biotechnology began to evolve.

Contemporary industrial biotechnology, by contrast, uses controlled and induced production of various microbial products. This is achieved through the choice of and, in some cases, the genetic manipulation of the producing organisms and the development of bioprocess engineering. Bioprocess engineering provides both sterile conditions and the control of several physiologically important parameters such as temperature (T), pH, dissolved oxygen (pO_2) and input of carbon and nitrogen sources, as well as other components. Today, such methods enable reproducible processes to be performed, thus ensuring product quality.

There are three phases in bioprocess engineering: upstream processing, bioreaction and downstream processing (Fig. 18.1). Upstream processing refers to all operations for the planning and preparation of the bioreaction. This includes the choice of a suitable biological system, the appropriate physiological parameters as well as the strain development. The practical preparation of the bioreaction—i.e. preparation of media, sterilization of bioreactor, preparation of precultures—also belongs to this step. During the bioreaction, a given substrate is converted into the desired product by a biological system. Microorganisms (bacteria, yeast, fungi), mammalian cells and enzymes may be utilized. As the resulting product typically comprises no more than 10–15% of the fermentation broth, downstream processing is needed in order to separate and purify the desired product.

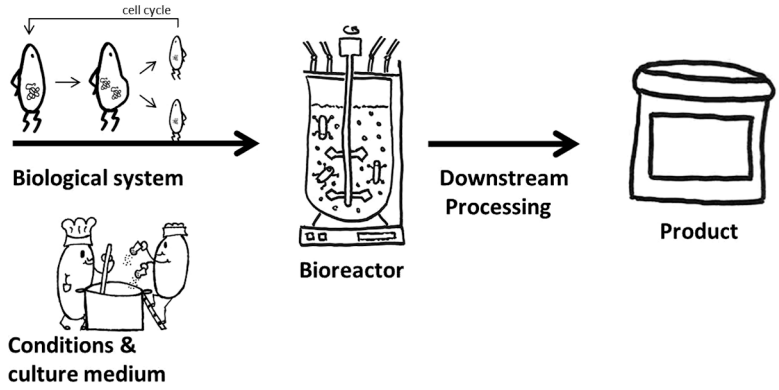


Fig. 18.1 Schematic overview of upstream, bioreaction and downstream processing in biotechnology. The choice of biologic system, as well as conditions and culture medium, belongs to the upstream processing. (© Johannes Kügler)

Do you want to learn more about the biotechnological conversion of renewable resources? Take a look at . Supplementary Video 18.1, a video from our MOOC "Concepts of Sustainable Bioeconomy" (2021).

18.2 Biological System

Bioprocess engineering employs biocatalysts, microorganisms and cell lines, or parts thereof, for the generation of value-added products. The huge potential of the multitude of naturally occurring organisms that could be used has not yet been exploited. The phylogenetic tree in Fig. 18.2 shows biotechnologically important groups of organisms found within the prokaryotes (cyanobacteria, proteobacteria, gram-positives) and the eukaryotes (fungi, animals and plants). For the choice of a suitable biological system, it is important that the organism is able to produce the desired product efficiently. The process conditions, such as temperature, pH and oxygen content, must be chosen according to the physiological requirements of the biological system employed.

18.2.1 Important Groups of Organisms for Biotechnology

The most important microorganisms for biotechnology are bacteria, yeast, algae and mammalian cells. Important *bacteria* used in industrial processes are, for example, *Escherichia coli* (for various processes e.g. recombinant proteins), *Bacillus* sp. (detergent proteases, vitamin B2), *Clostridium acetobutylicum* (acetone, butanol) and *Corynebacterium glutamicum* (amino acids). They are easily genetically manipulated, robust against shear stress, pressure and osmosis, show high productivity, cell densities and growth rates, and are able to grow in comparatively inexpensive media. One disadvantage is that they are often deficient in secretion of proteins and are not able to perform important posttranslational modifications such as N-glycosylation. The bacteria may become infected by phages, possibly destroying the bacteria culture and resulting in the loss of production.

Industrially employed *yeast and fungi* include *Saccharomyces* (beer and wine yeasts, ethanol), *Penicillium* (many antibiotics, e.g. penicillin) and *Aspergillus* (some antibiotics, many organic acids, e.g. citric acid). Their advantages are: high productivity of homologous proteins, high cell densities, very good secretion, fast growth rates, good pH tolerance (very important for the production of acids), large cell size (simplifies downstream processing), and no problems with phages. Additionally, yeast and fungi can perform posttranslational modification. However, their glycosylation pattern is neither identical nor similar to that of humans, and this limits their use in pharmaceutical products.

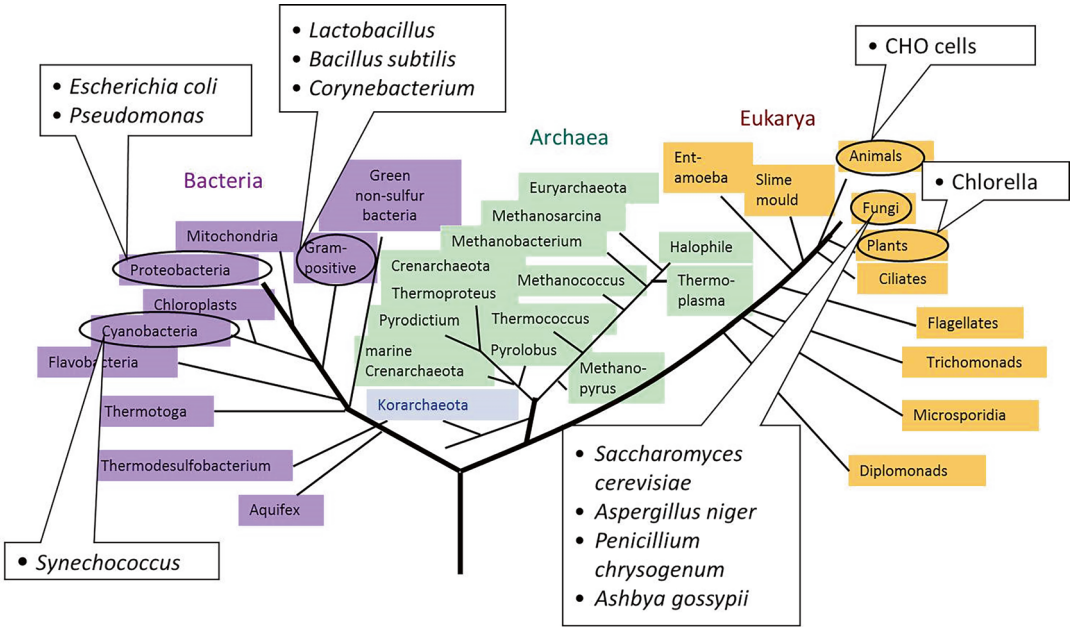


Fig. 18.2 Phylogenetic tree with important biotechnologically used microorganisms

The production of therapeutic glycoproteins for pharmaceutical use is performed by *mammalian cell* cultures. Various cell lines are employed industrially, the most relevant being Chinese hamster ovary cells (CHO), but also others to a lesser extent. Mammalian cell cultures are very sensitive in comparison to bacteria, yeast and fungi. They grow very slowly, have only low cell densities, are sensitive to shear stress and osmosis, and require high investment and process costs. However, one advantage is that they perform posttranslational modification and glycosylation pattern identical to those of humans. These properties make them the standard solution for therapeutic protein production.

Homologous proteins are proteins derived from the host strain's DNA.

Heterologous proteins are proteins derived from the DNA of another organism than the host strain in which it is expressed.

Posttranslational modification refers to modifications to the protein structure during protein synthesis. In protein synthesis, DNA sequences are first transcribed into RNA by RNA-polymerase and then translated into proteins by ribosomes. The protein's structure may then be modified, for example by the removal of *biochemical* groups or the addition of (in-)organic groups.

Glycolization/glycolization pattern is a specific posttranslational modification of the protein, in which sugar residues are attached to the protein. These sugar residues and their varying patterns are recognized by the immune system. It is thus mandatory that therapeutic proteins have the correct glycosylation and sugar residue pattern.

18.2.2 Strain Development—Genetically Improvement of Production Strains

Wild-type strains do not normally produce profitable quantities of the desired chemical substance. It may even be that the production strain does not naturally produce the desired substance at all. In order to enable production or improve their productivity, strains are genetically modified. This is called *strain development*. Methods used include classic screening and mutagenesis, genetic engineering, metabolic engineering (directed mutagenesis) and synthetic biology.

In *classical mutagenesis* (example: penicillin), the microorganism known to produce the desired substance is mutagenized by chemicals or UV light, which introduces random changes in the genome. A screening is then carried out to select enhanced producers. Mutagenesis and screening are traditionally repeated iteratively for several generations of microorganisms. This approach is very time-consuming. Another drawback is the introduction of several random mutations, which individually or collectively reduce the viability of the organism.

If the desired product is a direct gene product (i.e. a protein), *genetic engineering* is a suitable choice (example: insulin). Here, the gene encoding the desired protein is additionally incorporated via a vector or chromosomal integration into the production strain, which then produces it either intra- or extracellularly.

In *metabolic engineering*, the metabolic pathways of a microorganism are improved by the enhancement of desired pathways and deletion or attenuation of those that lead to by-products. Bottlenecks are identified through metabolic flux analysis (metabolomics and transcriptomics) and reduced by genetically enhancing biosynthesis routes. In this way, higher product titers (concentrations) with fewer by-products can be achieved (example: L-lysine and succinic acid).

The currently most modern approach is termed *synthetic biology*. In this approach, pathways are designed based on formerly gained knowledge (example: Propane-1,3-Diol, PDO) and the biosynthesis is reconstituted in the most suitable microorganism. Modified biosynthesis genes originating from various donors, including plants, may be exploited. Existing genome, metabolome, proteome and transcriptome data can be used in computational modelling for further enhancement. In synthetic biology, these data are used to design non-natural, novel pathways and circuits in production strains. These strains may then be used for industrial applications. Databases such as NCBI (National Center for Biotechnology Information), BRENDA (BRaunschweig ENzyme DAtabase), KEGG (Kyoto Encyclopedia of Genes and Genomes) and many others are essential for the design of such microorganisms.

18.3 Basics of Bioprocess Engineering

Bioprocesses are characterized by the utilization of living cells or enzymes as catalysts, which are therefore termed biocatalysts. The production of the biocatalyst is thus the first step in the conversion of a given substrate to a desired product.

18.3.1 Biomass Growth

Bacteria and yeast multiply by binary fission. Bacteria grow by cell enlargement and subsequent fission into two identical bacterial cells. Yeasts grow by budding: they divide into a mother and a smaller daughter cell, leaving a scar on the mother cell. The daughter cell grows to the same size as the mother cell. Fungi are multicellular organisms and grow either by apical growth or ramification, where a new cell is added to an existing one. The rate of growth in the reactor is called the specific growth rate (μ). This may vary in a given bioprocess, depending on nutrient availability, substrate inhibition, accumulation of metabolites (acetate, alcohol, lactic acid) and population density. Typically, different growth phases can be distinguished (see Fig. 18.3): Initially,

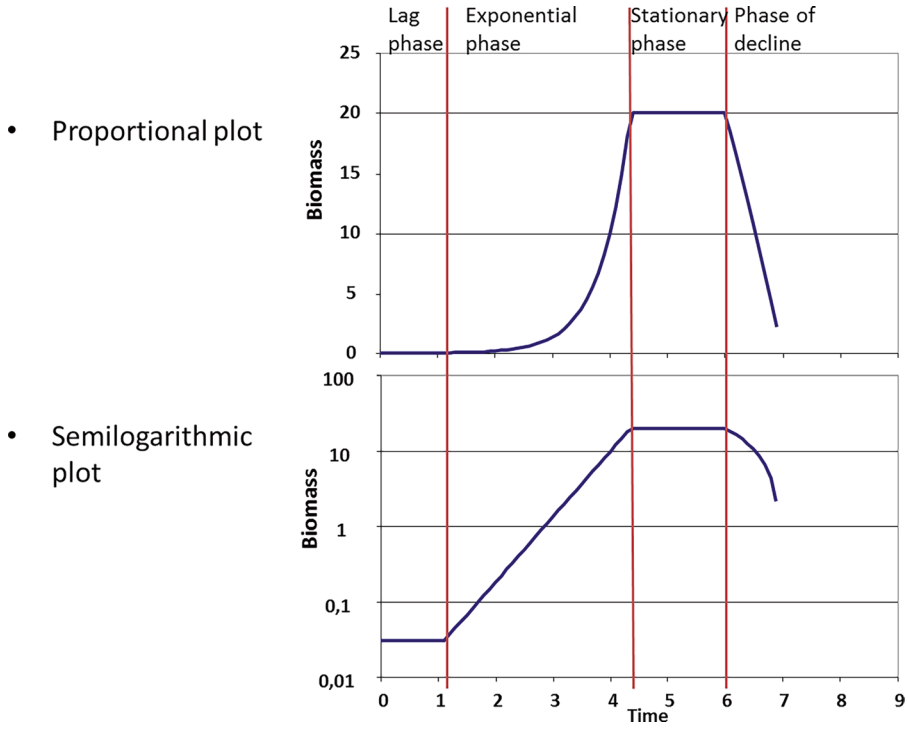


Fig. 18.3 Formal classification of growth phases

microorganisms adapt to the new environment, which is apparent in the so-called lag phase, where the growth rate is zero. This is followed by an acceleration phase with an increased growth rate. A subsequent phase with a constant growth rate, the exponential phase, is then observed. Population growth is finally limited by the consumption of available nutrients and levels off. In bioreactor cultivations, the rates of growth and product formation are controlled by the setting of process conditions and the feeding-in of nutrients.

18.3.2 Media Composition and Culture Conditions

In bioprocesses, the medium is the liquid in which the bioreaction is performed. It provides the microorganisms with an energy source and all necessary nutrients. Biomass is composed mainly of the elements carbon [C], oxygen [O], nitrogen [N], hydrogen [H], potassium [K], phosphorous [P] and sulphur [S] and other microelements. In order to produce biomass, all these elements have to be present in the medium in a suitable concentration. Additionally, other growth factors such as vitamins and essential amino acids may be required. If any of these are missing or have been consumed, the cell growth will stop. However, as the cells are still alive, they still consume nutrients for cell maintenance. For most biotechnological processes, the carbon and energy source consists of carbohydrates such as glucose, sucrose or starch, or carbohydrate residues such as molasses. They may also be provided by triglycerides such as vegetable oils. The nitrogen sources most often used are ammonia or ammonium salts, urea, corn steep liquor, yeast extract, soy flour, fish meal or protein hydrolysates. Media can be differentiated into complex and defined media. Complex media contain at least one non-defined component e.g. yeast extract or corn steep liquor. In a defined medium, the chemical composition of the carbon source, inorganic salts, as well as any other additions, is precisely specified. A defined medium is used when strict control and reproducibility

of the process are essential. Complex media are less expensive and can be used when strict control is not necessary.

Bioreactions have to be performed under physiological conditions, i.e. an environment that suits the microorganisms' preferences in terms of temperature, pH value, oxygen availability, ion concentrations and water activity.

Do you want to learn more about microorganisms and growth media for the production of biobased products? Take a look at Supplementary Video 18.2, a video from our MOOC "Concepts of Sustainable Bioeconomy" (2021).

18.3.3 Bioreactors, Process Kinetics and Process Control

Bioreactions are performed in a vessel called a bioreactor, which provides a sterile barrier, thus preventing contamination. A bioreactor can be understood as any defined space or apparatus in which material conversions take place with the participation of biocatalysts. Functions of bioreactors include mixing (homogenization) of content, suspension of solids (microorganisms, pellets), emulsification of two non-intersoluble liquids, dispersal of gases (air or O_2) in the liquid, ensuring that constant physical parameters (temperature, pH, pO_2) are in the optimal range. Therefore, devices for tempering, stirring, aeration, pH control, pO_2 control, foam control, and further addition of medium and acid or base are necessary. In this way, the processes can be controlled and reproduced. There are various types and shapes of bioreactors, including bubble column, fluidized bed reactor, tubular reactor (mainly for algae), and stirred-tank reactor (Fig. 18.4). The last is the type most often used.

Bioprocess kinetics describe the time-dependent courses of cell growth, product concentration and substrate concentration during a bioprocess. Important parameters include the specific growth rate μ [1/h], the substrate consumption rate, the product formation rate, the productivity P_v (g/L·h) and the product yield per substrate [$Y_{P/S}$ (g/g) or $Y'_{P/S}$(mole/mole)]. If investment and production costs are high, productivity is the most relevant parameter. If substrate costs are high, yield per substrate is most relevant.

Reactions can be performed in batch, fed batch or continuous mode. The easiest process mode is a batch culture, where the whole reac-

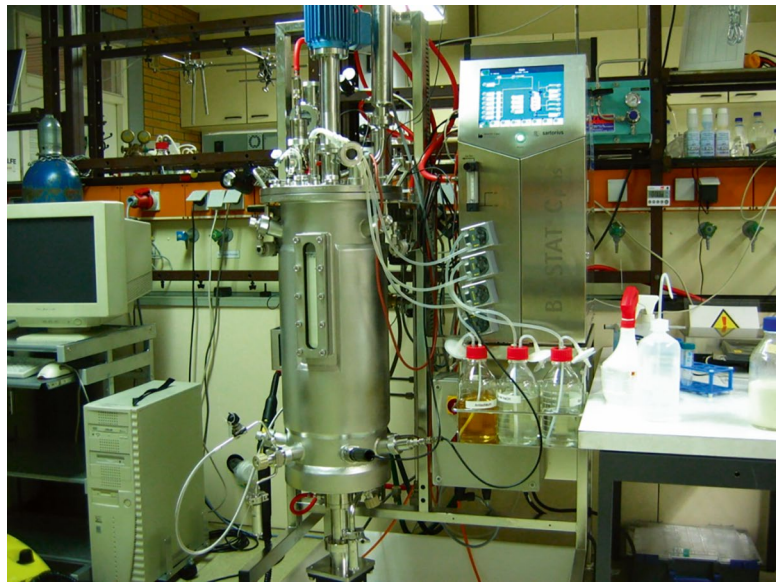


Fig. 18.4 A stirred-tank bioreactor for the controlled growth of microorganisms, with devices for stirring, O_2 and pH control, feeding-in of substrate, base and antifoam

tion is performed in the initial volume without further nutrient addition over time. The growth rate is not constant, as nutrients are consumed. Nutrients in excess may lead to metabolic overflow reactions. Fed-batch processes are started with a low volume and subsequent addition of nutrients. A constant or exponential growth rate can be achieved and metabolic overflow prevented. Correspondingly, the volume increases over time. A continuous culture enables a steady flow of fresh medium into and of bioculture out of the reactor. The volume remains constant, but the microorganisms grow at the set growth rate. With this kind of bioprocess, a quasi-steady state of biomass and nutrient concentrations can be achieved. Batch and fed-batch cultivations are advantageous where defined charges are required, e.g. in the pharmaceutical industry. Most industrially relevant bioproduction processes are carried out in fed-batch mode.

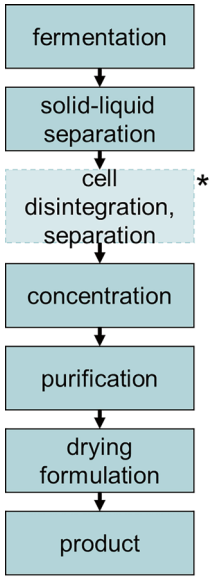


Fig. 18.5 General downstream processing scheme for a biotechnological product

18.3.4 Downstream Processing

Downstream processing deals with the recovery of the desired product. This is often an extensive task, as the fermentation broth consists of 90–99% water and hence the desired product is very diluted. In general, water has to be eliminated during downstream processing. Normally, further by-products are formed, which may be very similar to the target product. If, for example, an intracellularly produced heterologous protein is to be recovered, it has to be separated from numerous other proteins present in the cell, all consisting of chemically similar amino acid chains. For the recovery of the desired product, a generalized purification scheme can be followed, as shown in Fig. 18.5. The first step is nearly always a solid-liquid separation, where the solid biomass is separated from the surrounding liquid. If the target product is an extracellular compound, the biomass is discarded. If the target is an intracellular product, the supernatant is discarded. In the latter case, the cells are then disintegrated, and the solids are once again separated off and disposed of. In both cases, the remaining liquid is concentrated and then further purified in the next step. The degree of purification depends on the purity demands of the target product. For medical applications in particular, compliance with legislative regulations is cost-intensive. In the last step, the product is dried, formulated and packed, giving the final product, which is ready to be sold.

18.3.5 Possible Products

For the biological conversion of renewable materials, microorganisms are used as catalysts. As a rule, only naturally occurring metabolites and products can be produced so far.

These products are formed by metabolization of a given substrate (mostly glucose from starch hydrolysis) to the desired product. In the process, the substrate passes through different metabolic pathways, which can be classified as primary or secondary metabolism. In the primary metabolic pathways, intermediates and products of low molecular weight are formed, which are then either used for the generation of macromolecules or broken down to supply the cell with

energy. Examples of primary metabolic pathways are glycolysis and the citric acid cycle. Apart from fermentation end products, all primary metabolites are normally only synthesized in the amount required by the cell. Overproduction of these products can be achieved by modification of the metabolic regulation. For some primary metabolites, e.g. citric acid, the appropriate choice of fermentation conditions, such as low pH and excess substrate supply, leads to overproduction. Secondary metabolic pathways generate substances that do not appear to be directly needed for the survival of the organism. Secondary metabolites are often complex in structure and can be biologically active. One example of a secondary metabolism pathway is the mevalonate pathway, which leads to the production of isoprenoids.

Some metabolic pathways require oxygen for the transfer of electrons. In this case, aerobic conditions, i.e. with aeration, need to be provided. Other metabolites are formed in anaerobic conditions, so here no aeration is required. Not all microorganisms exhibit all kinds of metabolic pathways. There are strictly aerobic, facultative anaerobic, microaerophilic and strictly anaerobic microorganisms.

Possible products include *biomass*, as in baker's yeast and starter cultures, *primary metabolites* such as the end product ethanol and intermediates like organic acids and amino acids, *secondary metabolites* like antibiotics, alkaloids, toxins and biosurfactants, *specialty products* like storage substances, exopolysaccharides (e.g. xanthane), and pigments, *enzymes* like amylases, proteases, glucose isomerases and *proteins* like recombinant proteins or monoclonal antibodies.

18.4 Application of Industrial Biotechnology

This section presents bioproducts that have already been established.

18.4.1 Antibiotics

An antibiotic is a substance that either inhibits the growth of or kills a bacterium. There are several antibiotics on the market. The best-known is penicillin, which inhibits cell membrane formation and thus bacterial growth. Antibiotics have revolutionized the cure of bacterial infections. However, the spread of multi-resistance in pathogenic bacteria poses a global health threat, as the infections caused can no longer be treated with widely used antibiotics.

Penicillin was discovered by chance in 1927 by Sir Alexander Fleming. He noticed a fungal contamination growing on a bacterial culture. A halo with no bacterial growth had formed around the fungal (*Penicillium notatum*) colony. Flemming was able to produce an anti-bacterial extract with a titre of about 1.8 mg/L and named it penicillin. At first, penicillin was produced in surface cultures, making upscaling quite difficult. Nevertheless, as penicillin became important, especially for the cure of wounded soldiers, these surface cultures were performed industrially with high labour intensity in up to 100.000 milk bottles in parallel. With the development of bioprocess engineering and respective strains, it became possible to produce penicillin in submerged cultures, where the scaling-up of the tank is comparatively easy. New and more potent penicillin-producing strains were screened for. With improved strains and bioprocess engineering technology, the penicillin titre was increased by a factor of 40.000 within the following 80 years. Today, about 10.000 different microbial antibiotics are known. However, only a fraction of these is exploited for medical purposes.

18.4.2 Organic Acids

Organic acids are basic chemicals and serve as building blocks for polymers or as acidifiers. Most of them are produced chemically (e.g.

adipic acid), but citric, lactic, gluconic, itaconic, and succinic acid are almost exclusively produced biotechnologically. The four most important organic acids, each with a global production of more than one million tons per year, are acetic acid, acrylic acid, adipic acid and citric acid. Of these, only citric acid is produced biotechnologically.

18.4.3 Acetic Acid

About 7.000.000 tons of acetic acid are produced annually by chemical carbonylation of methanol. The conditions applied (150–200 °C and 3–6 MPa) are relatively mild for a chemical process. This reaction has a total carbon yield (Yc) of about 95%, i.e. 95% of the deployed carbon is converted to acetic acid. Biotechnological production by fermentation is modest in comparison: 200.000 tons of acetic acid as a component of vinegar. Vinegar is produced by employing bacteria of the genus *Acetobacter* or *Gluconobacter* in an incomplete oxidation of ethanol to acetate. This reaction has to be performed under aerobic conditions, as an oxygen molecule is added to the ethanol. The fermentation takes place at 26–28 °C at normal pressure. Even though the yield ($Y_{(P/S)}$) is 85–90%, the final concentration is only 100–150 g/L and the total carbon yield (Y_c) starting with glucose is about 57%.

Acetic acid is used in the food industry as acidulants, preservatives (E 260) and vinegar. The main fraction of acetic acid is used for the preparation of polymers, such as polyvinyl acetate (PVAC) for paints and varnishes; ethylene vinyl acetate and cellulose acetate for cigarette filters, films and other plastic products.

18.4.4 Succinic Acid

Succinic acid is one of the new substances that may pave the way to a bio-based industry. It can be used as a platform chemical to be transformed into further products. These may then serve as building blocks, e.g. in polymers. It can also be used directly as a monomer for alkyd and polyester resins; plasticizers; flexibilizers; paint solvents; food additives (E 363); flavour enhancers; potassium, calcium, and magnesium succinate as a substitute for sodium chloride and as an acidifier or acidity regulator. Succinic acid is a metabolite within the citric cycle and is gained under anaerobic conditions. Succinic acid can be produced by *E. coli* (company BioAmber), *Basfia succiniciproducens* (company Succinity, a joint venture between BASF and Corbion Purac) and *S. cerevisiae* (joint venture between DSM and Roquette). Whereas *E. coli* and *S. cerevisiae* had to be extensively genetically modified for high-titer succinic acid production, *B. succiniproducens* secretes it naturally in relatively high quantities. In *E. coli* and *S. cerevisiae*, the by-product formation is deleted and the biosynthetic pathway is enhanced. Under anaerobic conditions, the citric acid cycle is passed through in the reductive direction and succinic acid is formed and secreted into the medium as end product. Technically, this is realised in a two-phased bioprocess. For *E. coli* and *S. cerevisiae*, biomass is built up in the first phase under aerobic conditions. The second phase is the anaerobic production, where titres of about 100 g/L can be achieved.

18.4.5 Biopolymers

Nowadays, most plastics (300 Mt/a) are of petrochemical origin, and thus rely on a non-renewable resource. The terms "bioplastic" and "biopolymer" incorporate several concepts. One is the biotechnological manufacture of monomers used to produce bio-based synthetic materials such as lactic acid, propane-1,3-diol, succinic acid, isoprene, adipic acid, 1,5-diaminopentane and others. Bio-based synthetic materials may or may not be biodegradable. The term "biopolymer" also covers microbial polymers and, in general, polymers synthesized by living organisms such as polynucleotides (the nucleic acids DNA and RNA), polypeptides (proteins) and polysaccharides (polymeric carbohydrates). Biopolymers utilized as bioplastics are polyhydroxyalkanoates (PHA) such as polyhydroxybutyrate (PHB). However, the term "bioplastic" can also refer to a biodegradable

plastic of petrochemical or mixed origin. In this section, we will focus on bio-based synthetic materials. From an economic point of view, polylactic acid (PLA) (global production ~370.000 t/a in 2011) and xanthan (global production ~110.000 t/a in 2012) are the most important biopolymers.

18.4.6 Bio-Nylon and Diamines, Cadaverine

Nylon (PA66) was the first 100% synthetic fibre to be produced. It is a polyamide that can be spun and is produced by the condensation of two chemically produced monomers: 1,6-hexanediamine and adipic acid. Similar bio-based, or at least partly bio-based, products can be made by replacing the 1,6-hexane diamine by 1,5-diaminopentane and the adipic acid by either sebacic or succinic acid, to give the products PA 5.10 or PA 5.4. These bio-based polyamides can, for example, be used in textiles, carpets and sportswear. 1,5-Diaminopentane (cadaverine) can be produced biotechnologically. For this, the lysine biosynthetic pathway of *C. glutamicum* was extended by one step, the lysine decarboxylase. This product has been manufactured by BASF at pilot scale and processed together with sebacic acid derived from castor oil.

18.4.7 Polylactic Acid (PLA)

Polylactic acid (PLA) is a thermoplastic material with a rigidity and clarity similar to polystyrene (PS) or polyethylene terephthalate (PET). Its availability and attractive structure make it the frontrunner in the emerging bioplastics market. Its building block is lactic acid, produced by the fermentation of sugars. PLA is biodegradable and hence can be used for packaging material or single-use items, but also for household items. Lactide is formed by intermolecular dehydration of lactic acid. Polylactide (PLA) is prepared by catalytic ring-opening polymerization of lactide. Only the pure enantiomers, generally L-lactic acid, can be polymerized. Even though *Lactobacilli* are wild-type strains able to generate lactic acid, they are no longer used for large-scale lactic acid production. This is due to the product inhibition, pH sensitivity and susceptibility to phages. Today, genetically optimized *S. saccharomyces* strains are used, where an acetate dehydrogenase has been added to the genome. The advantages of this organism are its pH tolerance (> pH 2), no problems with phages and the simple downstream processing. Disadvantages are lower productivity, and that ethanol is formed as a byproduct.

18.4.8 Propane-1,3-Diol (PDO)

Propane-1,3-diol is a clear, colourless, odourless, biodegradable liquid with low toxicity. It is used in the manufacture of polyesters, for example, polytrimethylene terephthalate (PTT), also known as 3GT. From these polyesters, clothing, fibres, automotive parts, carpets, solvents and coatings are produced. Biotechnological production of PDO was the first industrial application of synthetic biology, as there is no organism known, which produces PDO directly from glucose. But it is known that *S. cerevisiae* converts glucose to glycerol and that the bacterium *Klebsiella pneumoniae* transforms glycerol to PDO. The cloning of the appropriate genes of both these microorganisms into *E. coli* gave a recombinant organism able to convert glucose to PDO. This is done in an aerobic process with a final concentration of 135 g/L propane-1,3-diol, a volumetric productivity (P_v) of 3.5 g/(L·h) and a yield ($Y_{P/S}$) of 51% (m/m). PDO biotechnologically produced from corn glucose was introduced in 2006 and is considered the first basic chemical produced by a strain generated by synthetic biology methods.

18.4.9 Isoprene

Currently, synthetic rubber (20 million t/a) is derived entirely from petrochemical sources and comprises mainly styrene-butadiene rubbers (SBR). Natural rubbers are isoprene rubber (IR), gained from plants like the rubber

tree (*Hevea brasiliensis*). Isoprene is a colourless liquid that is insoluble in water and volatile, as its boiling temperature is 34 °C. DuPont is working together with Goodyear on the development of a fermentation-based process for the production of bio-isoprene monomer (2-methyl-1,3 butadiene). The largest application area for bio-isoprene isthe production of synthetic rubbers for "green" tires and elastomers. Two metabolic pathways exist, which lead to isoprene as a secondary metabolite: the mevalonate (MVA) pathway and the methyl-erythritol-4-phosphate (MEP) pathway. For the fermentative production, an *E. coli* was chosen as the production strain. The MEP pathway is endogenously present in *E. coli*, and the MVA pathway was additionally cloned into it. Later, an adapted isoprene synthetase was added to the genome. With this strain, an isoprene titer of 60 g/L and a volumetric productivity (P_V) of 2 g/(L·h) was achieved. The yield ($Y_{P/S}$) was 11% isoprene per glucose. This is quite ineffective, given that the theoretical maximum is 24% for the MVA pathway and 29% for the MEP pathway. Isoprene is gaseous at 37 °C and therefore can be continuously removed from the exhaust gas of the bioreactor.

18.4.10 Polyhydroxyalkanoate (PHA)

Polyhydroxyalkanoates are microbial polymers (polyesters) produced by bacterial fermentation of sugars. Polyhydroxybutyric acid was discovered in 1926 in *Bacillus megaterium*. Numerous bacteria (>90), including *Cupriavidus necator,* form PHAs as a reserve or storage material. PHAs are therefore fully biologically degradable and have further useful properties such as thermoplasticity, biocompatibility and non-toxicity. In 1990, the first biodegradable product (Biopl®) was launched in Germany. However, the plastic recycling system ("Gelber Sack") introduced here a year later inhibited the advance of this bioplastic. Today, PHA products are insignificant. Nevertheless, Metabolix has successfully commercialized PHA biopolymers for a range of applications. PHAs are considered a replacement for petrochemical polymers. Their potential applications include packaging material, hygiene products and medical industry products.

18.4.11 Biofuels

Biofuels are renewable fuels derived from biomass through chemical or biochemical reactions. Depending on the feedstock used, three generations of biofuel can be differentiated. "First-generation" biofuels are based on food crops, such as sugar cane and corn, and are thus in direct competition with food. "Second-generation" or "advanced" biofuels are based on non-food crops and lignocellulose with reduced or no food competition. "Third-generation" biofuels are based on algae, which avoids competition with food and lowers land requirements. The main biofuel used today is ethanol. Other biotechnologically producible biofuels are biobutanol, alkanes, biodiesel and biogasoline. For biobutanol production, either *Clostridium acetobutylicum* or metabolically engineered *S. cerevisiae* can be used. As a proof of principle for microbial alkane production, the metabolic pathways of alkane production from cyanobacteria were functionally expressed in *E. coli,* which secretes the hydrocarbons. The company LS9 was heading towards commercialization of these microbial fuels, but the production was stopped as it proved uncompetitive with petroleum-based fuels.

Do you want to learn more about microbial biosurfactants? Take a look at Supplementary Video 18.3, a video from our MOOC "Concepts of Sustainable Bioeconomy" (2021).

18.5 Conclusion and Outlook

Currently, industrial biotechnology only accounts for a minor proportion of industrial chemical and material production. In comparison to petrochemical industries, biotechnology only holds a representative market

share in a few niche areas. Thus, a major turnaround will be required to convert a major part of the current chemical industry towards a bio-based one. However, the potential exists for novel, environmentally friendly, knowledge-based products and this potential could generate new, high-level job opportunities for biotechnologists and bioeconomists in the future.

Questions

1. Differentiate between "traditional biotechnology" and modern biotechnology by means of an example.
2. Various microorganisms are applied in the industrial production of bioproducts. Assess the advantages and disadvantages of the most important organisms.
3. In a few niche areas, biotechnologically derived products hold a representative market share. Compare and contrast an established with a prospective bioproduct. Consider factors hindering or facilitating the introduction.

Answers

1. Historically, biotechnology dealt with uncontrolled food processing, such as in the production of wine, beer, vinegar, bread, cheese and other fermented foods. Modern biotechnology, however, uses controlled and induced production of various microbial products through methods such as genetic manipulation and bioprocess engineering. For example, Louis Pasteur's discovery of yeast in beer brewing represents traditional biotechnology, whereas the production of insulin via genetic engineering exemplifies modern biotechnology.
2. The following microorganisms are applied in the industrial production of bioproducts:
   - **Bacteria**: Advantages include high productivity, cell densities, and growth rates, and the ability to grow in comparatively inexpensive media. However, they are often deficient in the secretion of proteins and are not able to perform important posttranslational modifications such as N glycosylation.
   - **Yeast and Fungi**: Advantages include high productivity of homologous proteins, good pH tolerance, and no problems with phages. A disadvantage is that their glycosylation pattern is neither identical nor similar to that of humans, limiting their use in pharmaceutical products.
   - **Mammalian Cells**: They perform posttranslational modification and glycosylation patterns identical to those of humans. However, they grow very slowly, have only low cell densities, and require high investment and process costs.
3. One possible comparison of an established and prospective Bioproduct may focus on the following two examples:
   - **Established Bioproduct (Penicillin)**: Penicillin has revolutionized the cure of bacterial infections and is produced in large-scale submerged cultures. Factors facilitating its success include improved strains and advances in bioprocess engineering.
   - **Prospective Bioproduct (Isoprene)**: Isoprene is being developed for synthetic rubbers for "green" tires, but its production faces challenges, such as ineffective yields and competition with petrochemical processes. Factors hindering its introduction include its low yield of 11% compared to the theoretical maximum of 29%.

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Thermochemical Conversion

Andrea Kruse



Fig. 19.0 Thermochemical conversion. (© Andrea Kruse) (▶ https://doi.org/10.1007/000-hv0)

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/978-3-032-09098-0_19. The videos can be accessed individually by clicking the DOI link in the accompanying figure caption or by scanning this link with the SN More Media App.

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All thermochemical conversions help to overcome two main hurdles in the bioeconomy: the high oxygen content of biomass (low heating value if used as fuel) and the large variability in biomass composition and characteristics. This means, all thermochemical conversions have in common that they can produce platform chemicals, materials or fuels from a wide range of biomass types, and that the oxygen content is lower in the product than in the feedstock. The bioeconomy is not only a concept but also requires technologies that are attractive enough for companies to put into practice, thus creating the technological base for a large-scale use of biomass. For the substitution of fossil resources by biomass, new technologies are needed. In this chapter, students learn how biomass is converted by (thermo-)chemical conversion technologies to energy carriers or platform chemicals. One example is the conversion of chicory roots to the platform chemical hydroxymethylfurfural (HMF). After further chemical conversion, HMF can be used to produce a wide range of common objects from daily life, including bottles and stockings. Thermal conversion can also be applied to produce special carbon materials, e.g. supercapacitors, which will enable a more flexible use of E-cars.

Learning Objectives

After studying this chapter, you will…

- …be able to name and describe different thermochemical conversion technologies (see ► Sects. 19.1, 19.2 and 19.3).
- …be able to illustrate the range of products which can be produced by thermochemical conversion (see ► Sects. 19.1, 19.2 and 19.3).
- …be able to choose an appropriate conversion process with respect to a given feedstock and desired product (see ► Sects. 19.1, 19.2 and 19.3).

When biomass is compared with fossil resources such as coal or oil, the main difference is its higher oxygen content. Cellulose, the main component of biomass, contains one oxygen atom per carbon atom, which reduces the heating value of biomass when used as fuel. The high oxygen content is also a disadvantage when biomass is used as a source of chemical compounds to produce, for example, plastics. ◘ Figure 19.1 displays a small part of cellulose using Lego® bricks to demonstrate its structure. Every red brick (which represents a carbon atom) has a hydroxy-group (OH) attached to it. In chemistry, this is called a functional group, which, put simply, means 'a place to make chemical bonds'. As can be seen, cellulose has a functional group at each carbon atom and is therefore considered 'over-functionalised'. For plastics, every basic chemical needs to have two functional groups, one at each end. This enables the formation of long chains, which are the basis of all polymers. In fact, this is what the word polymer means: a long chain of repeating units.

In principle, there are three possibilities to convert biomass into products: (1) biological or biochemical methods applied at low temperatures, as shown in ► Chap. 18, (2) chemical conversion at medium temperatures, and (3) thermochemical processes at higher temperatures. This chapter focuses on thermochemical processes, which refer to chemical conversions that use heat as a crucial tool for the conversion. Thermochemical conversions are characterised by the desired product and the 'agents' added to influence the reaction. The products are solids (char, coke, charcoal), a tarry liquid and gases. Important agents include oxygen and air. The addition of these leads to a partial combustion of organic material, delivering the heat necessary for the conversion. This is then called an *autothermic process*. Another important agent is water, added as a liquid or in the form of steam. Due to the large range of processes which are performed with or without water, the following sections distinguish between *dry*, *steam-assisted* and *hydrothermal biomass conversions*. All conversions methods have one thing in common: the oxygen content is reduced, as illustrated in ◘ Fig. 19.1 for charcoal formation.

Fuels can be characterised by the ratio of hydrogen to carbon and the ratio of oxygen to carbon, which can be displayed in so-called van Krevelen diagrams. ◘ Figure 19.2 shows

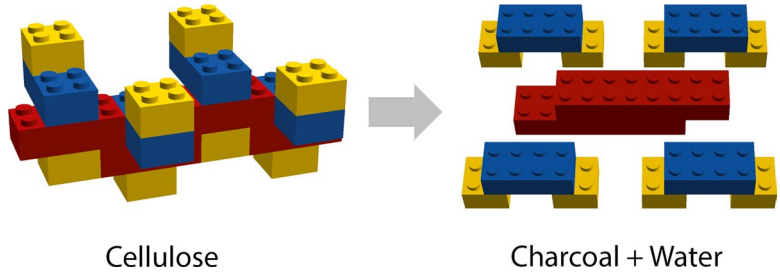


Fig. 19.1 Charcoal formation from biomass, illustrated using Lego® bricks. Red bricks represent carbon atoms, blue oxygen atoms and yellow hydrogen atoms. (© Andrea Kruse)

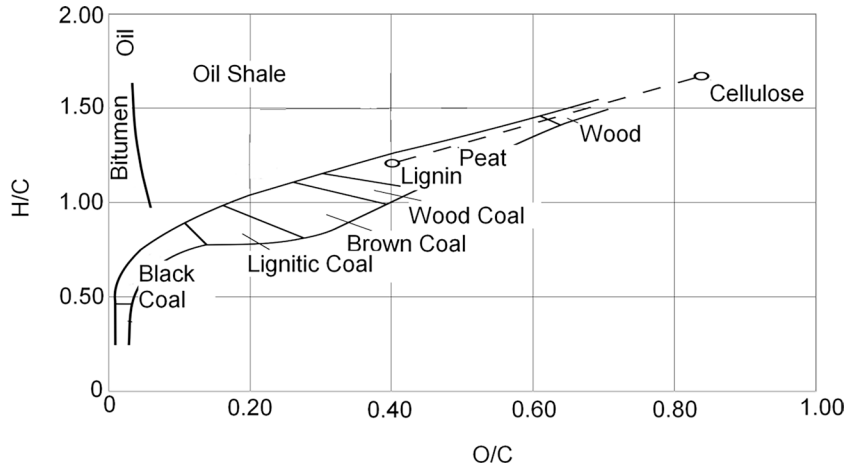


Fig. 19.2 Van-Krevelen diagram of fossil fuels and biomass

different types of fossil coal and fossil oil, as well as wood, as an example of biomass.

Biomass materials used for thermochemical conversions mainly consist of hemicellulose, cellulose, lignin and ash. Cellulose and lignin have also been added to the van Krevelen diagram (Fig. 19.2) above. Lignin has a chemical composition similar to brown coal. As can be seen, fossil coal has both a lower oxygen and hydrogen content in relation to carbon compared to cellulose. A line could be drawn from cellulose to coal in Fig. 19.2, corresponding to the elimination of water, as shown in Fig. 19.1. It should be pointed out here that the production of a liquid product similar to fossil oil can only be achieved by the addition of hydrogen, e.g. by coal hydrogenation. A conversion that eliminates oxygen only, instead of water, is not chemically possible. The only possibility of reducing the oxygen content without reducing the hydrogen content is through the elimination of carbon dioxide or carbon monoxide. Here, methane or hydrogen are the other end products, not hydrocarbons.

19.1 "Dry" Processes

Dry thermochemical conversion processes are considered the more 'traditional' conversion processes. For dry processes (Fig. 19.3), the water content of the biomass needs to be below 10 wt. %, which implies that the processes can only be applied to biomass with low water content, such as wood, straw, as well as crops which produce similar biomass (e.g. miscanthus). Other biomass feedstocks with

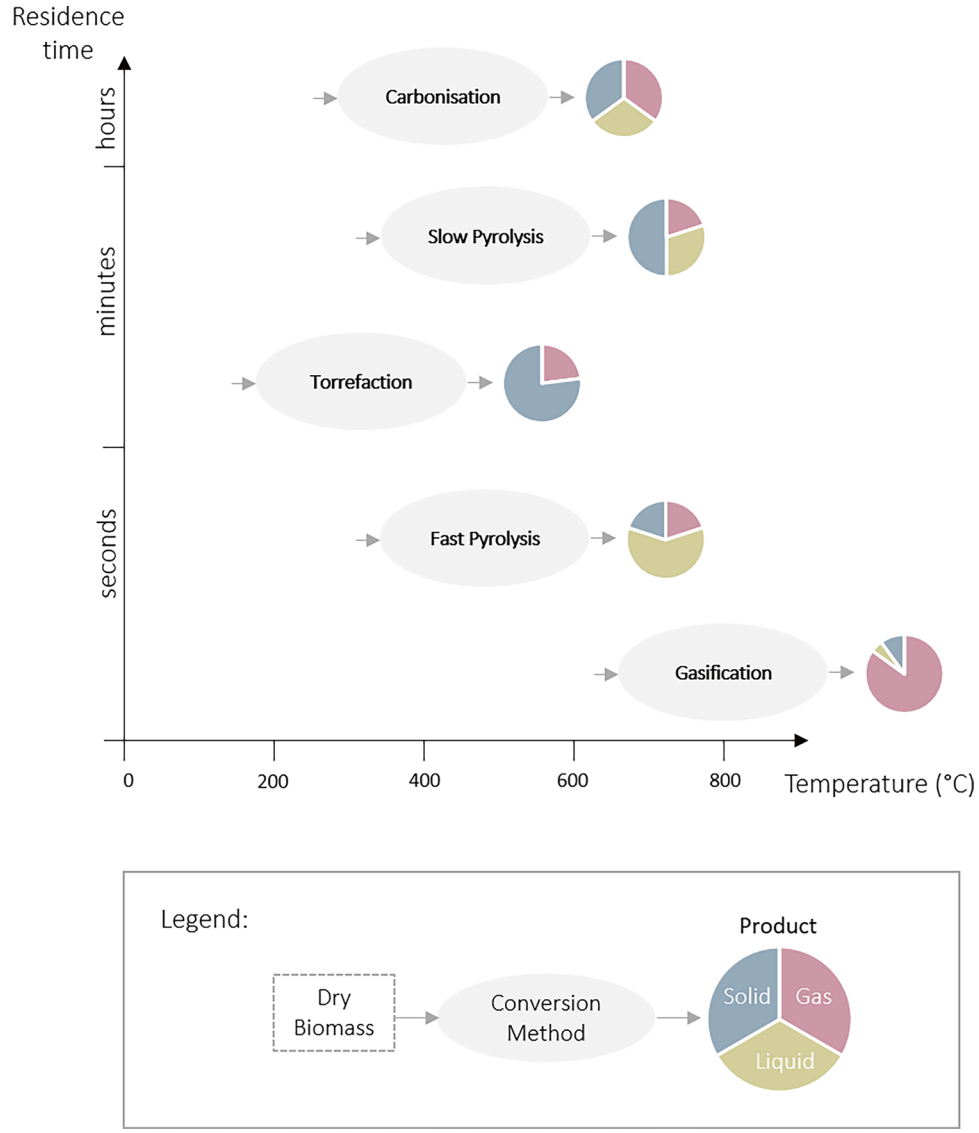


Fig. 19.3 Thermochemical conversion: overview of dry processes

higher water content must be dried before being processed. As drying requires a lot of energy, it is not usually done in practice. The dry processes are summarised in Table 19.1

Dry biomass conversion generally leads to the formation of a mixture of solid, liquid and gaseous products, the ratio of which changes with reaction conditions (Table 19.1). At the lowest temperatures of around 300 °C, so-called torrefaction occurs. For this, continuous reactors like rotating tubes are often used. From a chemical point of view, the heating process first dries the biomass, then leads to the formation of volatilised compounds from hemicellulose to leave a solid, partially charred material. At higher temperatures, cellulose also forms volatiles and starts charring. The condensable and burnable permanent gases are combusted outside the torrefaction plant to generate the heat required for the process. Torrefaction is usually regarded as a pre-treatment process

Table 19.1 Overview of dry processes (based on Hornung 2014)

	Conditions	Liquid(tar with water)	Solid(char)	Gas
Fast pyrolysis	~500 °C, short hot vapour residence time < 2 sec.	60%	20%	20%
Slow pyrolysis	~500 °C, ~ 1h	30%	50%	20%
Torrefaction	~300 °C, ~10-30 min		77%	23%
Slow – Carbonisation	~400 °C, ~hrs/days	30%	35%	35%
Gasification	~800 °C	5%	10%	85%

and is followed by another thermal treatment, e.g. gasification or combustion. The torrefied product has a slightly higher heating value than the original biomass as it has a lower oxygen content (e.g. 19 MJ/kg to 20–22 MJ/kg (Gucho et al. 2015)). This reduces the relative transport costs. In addition, the structural changes that occur during torrefaction result in far less energy being required for milling.

Slow pyrolysis is applied to obtain a solid fluid and to reach complete conversion. Here, temperatures of 500–600 °C and longer reaction times lead to a complete charring of the biomass. Many different types of slow pyrolysis reactors have been developed (Demirbas et al. 2016; Kan et al. 2016), yet typically rotating tube reactors are used, and the combustible gases are used for heat generation. The classic process to produce charcoal is by using a kiln. In the kiln, first, a high amount of air is introduced so that part of the volatiles formed by wood pyrolysis are burned. Once a high temperature has been reached, the air supply is reduced. Charring then occurs over the course of several weeks. A large amount of tar compounds and particles leave the kiln with the gases, as no gas cleaning takes place. A more advanced version of the process uses a retort. Here, the reaction time is reduced to hours, and no oxygen/air is added. The volatiles are combusted outside the retort in a burner, and the off-gas is used for heating. There are virtually no emissions of tarry or hazardous compounds (see also Quicker and Weber, 2016).

> ***Pyrolysis*** is the conversion of biomass with heat and no or low amounts of oxygen to avoid combustion.

Charcoal is used to produce activated carbon, e.g. as a feed additive, in medicine, as a basis for catalysts, and for gas and water cleaning. It also forms the basis of black powder in fireworks and is used for metallurgical purposes, e.g. the production of copper. Today, the production of advanced carbon materials, such as supercapacitors, electrodes for fuel cells and hydrogen storage as well as modern battery parts, is of particular interest (see also Tiwari and Shukla 2014) (Fig. 19.4).

> ***Carbonisation*** is the reaction of biomass leading to a higher carbon content. Charring is a special case of carbonisation, usually at around 500 °C and "dry".

In the case of complete conversion of biomass at around 500/600 °C, tar can be

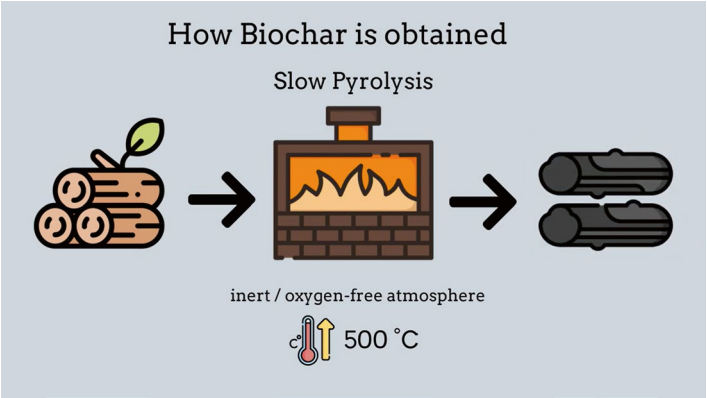


Fig. 19.4 Biochar production and utilisation. © Universität Hohenheim, Krishna Sangam & Philipp Konnerth (► https://doi.org/10.1007/000-hty)

regarded as intermediate. The mixture containing hundreds of different compounds reacts further by polymerisation processes to form coke and by further splitting to gases. Therefore, if this tar or so-called pyrolysis oil is the desired product, fast heating up to 500–600 °C, a short reaction time of a few seconds and quenching for fast cooling down is applied (Table 19.1). This is necessary to avoid consecutive reactions to coke and gases. While the formation of char and gases cannot be avoided completely, the yields of pyrolysis oil can be maximised by a short and defined reaction time. From the point of heat transfer, fast heating-up is only possible by solid–solid contact. Therefore, in all types of reactors applied, biomass is heated up by direct contact with a hot surface, either consisting of metal or sand particles. Usually burners, that burn the gases coming out of the process, generate the necessary heat. At reaction conditions, the pyrolysis oil is turned into a condensate in one, two or more steps, after separation of the char/coke particles by cyclones. If the water content is low, condensation of the pyrolysis oil is possible without phase separation in one step. Pyrolysis oil usually has a water content of 20–30% (g/g) (Bridgwater et al. 1999; Oasmaa et al. 2003). This water is partly a product of the reactions and originates from moisture in the biomass, together with high amounts of polar compounds such as acids, sugars, aldehydes and ketones. Various types of phenols are also found in pyrolysis oil. If the water content is increased to above ~ 45%, phase separation occurs with the formation of an aqueous and organic phase. In addition, a lignin-like solid is precipitated. Therefore, in the case of relatively high water content, it is useful to use a two-step condensation process. Here, an aqueous phase with high contents of acetic acid and an organic phase are produced (Dahmen et al. 2010). Pyrolysis products can be upgraded to fuels, for example, for the transport and aviation sector, which requires large amounts of hydrogen (Wildschut et al. 2009). Pyrolysis oil from wood, or one fraction of it, is used as "liquid smoke" in the food industry or as a lure to attract boars during hunting.

In the *bioliq® process* (Dahmen et al. 2012), the first step of biomass conversion is fast pyrolysis and the second gasification. This addresses one of the principal challenges of biomass conversion process chains – the widespread, decentralised occurrence of biomass – by splitting the biomass conversion in two steps, fast pyrolysis and gasification. The goal of the bioliq® process is to produce a fuel via syngas. To achieve economies of scale, the gasification and synthesis plant needs to have a high throughput, which requires the biomass to be supplied from a very large area. However, the amount of energy necessary to transport

biomass – a material of relatively low heating value (16–19 MJ/kg, dry matter) – over long distances to supply a large gasification plant is very high. In the bioliq® concept, the biomass is first pyrolysed in smaller, fast pyrolysis plants. Then the coke and the pyrolysis oil are mixed to a slurry. This slurry has an energy density ten times higher than that of straw, the biomass used as feedstock. The slurry is then transported to the gasification plant. In this case, a gasification temperature above 1000 °C is required to avoid tar formation.

The products resulting from gasification of biomass, for example in the bioliq® process, are very important in the bioeconomy for the substitution of fossil fuels by biomass. Gasification to produce syngas and the subsequent use of syngas to produce different products are common processes in today's industry. Usually, coal or residues from fossil oil processing are gasified. Therefore, the resource may be changed to biomass to which the available processes for converting syngas can be applied without further need for adaptation. These processes include ammonia production, methanol production, Fischer-Tropsch synthesis to produce diesel fuel, or synthesis to produce aldehydes, ketones and other compounds. Besides air or oxygen, water or carbon dioxide are also added as a so-called 'gasification agent' (Hofbauer 2009). The addition of water increases the yield of hydrogen.

19.2 Steam-Assisted Processes

For conversion processes that use lower temperatures than gasification, for example pyrolysis, water is added. This alters the gas composition by increasing the hydrogen yield. In addition, the heat transfer is improved. The required heat transfers from outside a biomass particle to inside and inside the solid particles represent the limiting steps for the conversion of biomass during slow pyrolysis and torrefaction. By adding water in the form of steam, a high carbonisation conversion of biomass is achieved at lower reaction temperatures compared to the conversion without steam addition simply by improving the heat transfer (Pütün et al. 2006).

Excursus 19.1 Nutrient Recovery

During high-temperature dry conversions, plant nutrients like phosphates are part of a glass-like slag. They are not available for plants directly. During low-temperatures dry conversions, nutrients like phosphate leave the reactor with the char and must be leached by strong acids or used together with the char. During hydrothermal conversions (▶ Sect. 19.3, below), the situation is completely different: Hydrothermal carbonisation offers the opportunity to recover around 80% of phosphate as pure fertiliser. During hydrothermal liquefaction, nutrients stay dissolved in water, and can be used, e.g. for algae growth (Lopez Barreiro et al. 2015). In supercritical water, salts, which are the nutrients, precipitates and can be removed from the reactor. Usually, these salts can easily be solved again and are easily available for plants.

19.3 Hydrothermal and Supercritical Water Processes

A special case of water being used as an agent in biomass conversion is the reaction in liquid or supercritical water as a reaction medium. Biomass conversions in liquid water at increased temperatures are called *hydrothermal*. This expression originates from geology, where it refers to reactions in liquid water at increased pressure and temperature. Depending on the temperature required, the pressure must be adapted to avoid evaporation. An overview of hydrothermal processes is given in ◘ Fig. 19.5.

In addition to the different conversion processes, ◘ Figure 19.5 includes the vapor pressure curve of water, ending in the critical point. All processes, except the supercritical one are conducted in liquid phase, at pressure above the water vapor pressure at this temperature. The higher the temperature, the higher pressure needed to have liquid water as a reaction medium. If the critical point is reached, the phase boundary between gaseous

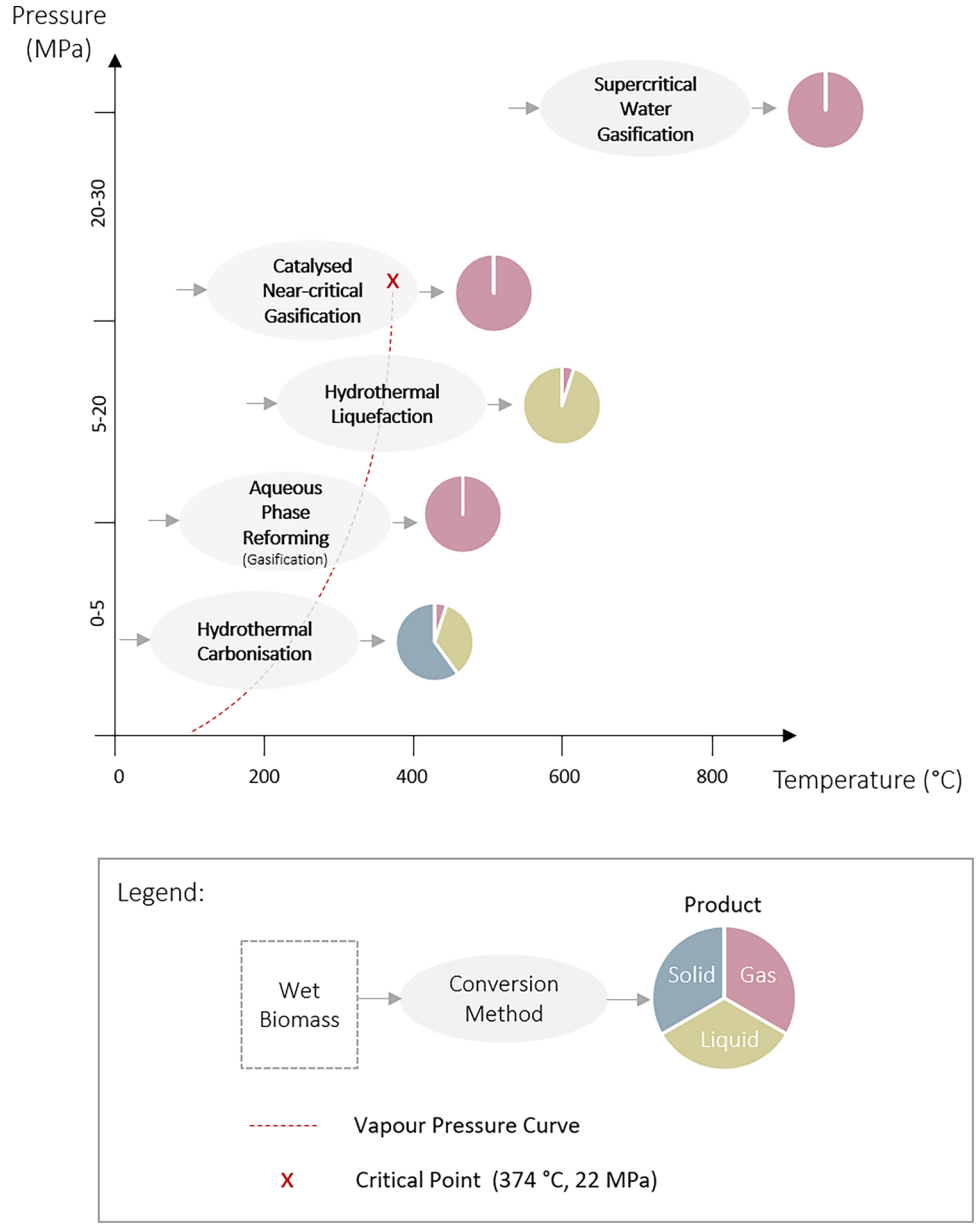


Fig. 19.5 Thermochemical conversion: hydrothermal and supercritical water processes

and liquid states no longer exists. This is called *supercritical region*.

> ***Supercritical water*** is water at a temperature above 374 °C and a pressure above 22 MPa. It has the solvent behaviour of a non-polar solvent such as pentane.

By adapting the pressure, a supercritical medium can be changed from liquid-like to gaseous-like density, without the appearance of a phase boundary.

It may seem surprising that in Fig. 19.5, different processes with fairly similar reaction conditions are displayed next to one another. In addition, the subcritical processes are all in the liquid region. This is due to the special

properties of water, which change with temperature. Subcritical water has a higher ionic product, behaving like a mixture of a weak acid and a weak base. Therefore, reactions, which usually require the addition of an acid or base, may occur without these additions. In contrast, in supercritical water, the ionic product is very low. This means that, per definition, no Brønsted acids (compounds that produce H^+ ions in water) or bases can't exist anymore. On the other hand, the solvent polarity of water decreases with temperature, although water remains a polar and very reactive molecule. The reason for this is the lower interaction of the water molecules with each other as well as their faster thermal movement. As a consequence, the solubility of gases and non-polar compounds increases, and the solubility of salts decreases. At around 30 MPa, supercritical water behaves like pentane, with complete miscibility with gases, very good solubility of non-polar compounds, and very low solubility of salts (Kruse and Dahmen 2015).

Hydrothermal and supercritical water processes are of special interest for the use and conversion of 'wet biomass'. A living plant has a water content of 80–90%. Many biomass residues from agriculture and the food industry, as introduced in ▶ Chap. 12, also have such high water contents. This kind of biomass can be converted by digestion. In this case, methane is the desired product, but the conversion is not complete because lignin and some types of fibres cannot be digested. The biomass could be dried if other products than methane are desired and a complete conversion is strived for, at the cost of large amounts of energy for drying. In hydrothermal processes, wet biomass is converted without drying and the water in the biomass becomes the reaction medium. Therefore, from a chemical point of view, hydrothermal processes are completely different from dry processes. In hydrothermal processes, the polar water molecules split the polar bonds of the biomass by hydrolysis. In contrast to dry processes, which are mainly solid-gas reactions, hydrothermal conversions usually occur in one phase, with fast degradation of the solid biomass by reaction with water. The fast splitting of biomass in water is the reason for the lower temperatures needed at hydrothermal conversions compared to dry processes. On the other hand, the high pressure is often regarded as disadvantage of hydrothermal conversions of biomass, as feeding may be a challenge (Kruse and Dinjus 2007).

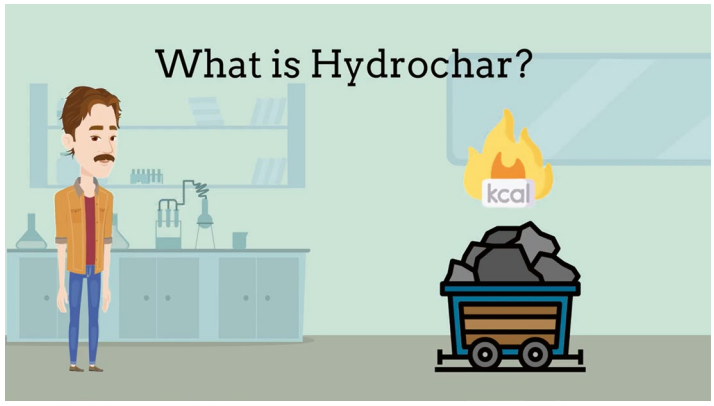


Fig. 19.6 Hydrochar production. (© Universität Hohenheim, Krishna Sangam & Philipp Konnerth https://youtu.be/8kEbmdWUfDE?si=dHcQt9OZJUc3vPXQ) (▶ https://doi.org/10.1007/000-htz)

Hydrothermal refers to reaction conditions in liquid water at temperatures above 100 °C and at increased pressure.

Hydrothermal carbonisation occurs at temperatures typically in the range of 180–230 °C. Most of the carbohydrates, possibly even the complete biomass, are hydrolysed and dissolved. The desired product, called HTC-coal or hydrochar, is formed via polymerisation (Titirici et al. 2015a, b, see video in Fig. 19.6). This process has been further developed, e.g. to produce supercapacitors to store electricity from renewable resources or in electric cars (Titirici et al. 2015a, b).

Hydrothermal liquefaction occurs at around 300 °C in liquid water, often in the presence of alkali catalysts. Here, biomass is completely converted to smaller molecules like substituted phenols, different acids or other carbonyl compounds. This process was developed under the trade name "hydrothermal upgrading" by the company Shell (Goudriaan and Peferoen 1990). There are three differences between hydrothermal liquefaction and fast pyrolysis, which also produces a liquid or 'tarry' mixture from biomass. First, the process temperature of the hydrothermal method is very low. During flash pyrolysis, temperatures of around 500–600 °C, much higher than for hydrothermal liquefaction and very short reaction times of a few seconds are applied. The short reaction times are necessary to avoid char/coke formation. Such limitations do not exist for hydrothermal liquefaction—which is the second difference between hydrothermal liquefaction and fast pyrolysis—where a wide range of reaction times may be applied. Thirdly, during dry flash pyrolysis, large amounts of solid and gaseous products are formed. Hydrothermal liquefaction in contrast leads to a low gas yield, consisting mainly of carbon dioxide with no energy content, and very low solid yields. The solids formed are often salts. In the reaction conditions, the tarry compounds are dissolved in water. After cooling down, the tarry liquid phase separates from the aqueous phase. Through this separation, the phenols formed from the biomass are concentrated in the tarry phase. Acid and other polar (i.e. oxygen-containing) compounds stay in the aqueous phase. Phase separation may take some time, but it leads to a tarry product with a high heating value. This heating value is higher than that of the tarry product of fast pyrolysis. In addition, the water content of hydrothermally produced oil is very low (<0.5% (g/g) for complete phase separation) compared to fast pyrolysis oil (20–30%). The reason for this is simply that all polar compounds are in the water, not in the oil. A minor disadvantage of the low water content is the rather high viscosity of hydrothermally produced oil (Lopez Barreiro et al. 2014; Lopez Barreiro et al. 2005b). It usually flows above 80 °C. To decrease the viscosity and to obtain a more diesel-like fuel, this oil is hydrogenated. The product is called "HTU-Diesel" and in the Netherlands, large efforts have been made to establish such a process. Due to the relatively low oxygen content, such a process is energetically and economically more interesting than for pyrolysis oil. Today, hydrothermal liquefaction is often used for the conversion of algae (Valdez et al. 2014; López Barreiro et al. 2015a, b). The reasons for this are:

1. Algae are very wet biomass and should be converted into water.
2. Fast-growing algae are usually rich in carbohydrates, and the lipid content is too low for the production of biodiesel.
3. The aqueous phase contains various nutrients (minerals) which can be recycled (López Barreiro et al. 2015a).

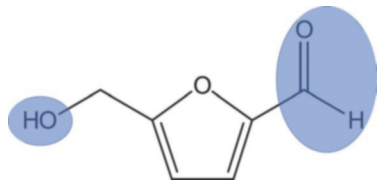
The basic studies on hydrothermal liquefaction were done with wood. Wood is not a typical 'wet' biomass. The use of relatively dry wood opens the opportunity to recycle water, as wood has a relatively low water content. In the case of wet biomass, the water coming out of the process must be 'cleaned', e.g. by digestion. Hydrothermal liquefaction with a throughput of 100 kg/h has been demonstrated in Apeldoorn, Netherlands (Goudriaan and Peferoen 1990). A special case of hydrothermal liquefaction is the hydrolysis of lignin to obtain phenols. Here, temperatures of around 400 °C are usually applied because of the lower reactivity of pure lignin than lig-

nocellulose. In addition, hydrogenation e.g. by hydrogen and catalyst addition is conducted. Phenols are interesting platform chemicals for resin production.

Another special case of liquefaction is the production of hydroxymethylfurfural (HMF, see ◘ Fig. 19.7) from sugars. HMF is one of, or perhaps the most interesting, platform chemicals for the bioeconomy (Teong and Zhang 2014), mainly due to its two functional groups that enable the formation of many different consecutive products. These chemicals can replace fossil-based plastics, and potential end products include bottles for drinks and nylon stockings. HMF can be produced in hydrothermal conditions (Antal et al. 1990; Yin and Tan 2011) and is assumed to be an intermediate product of hydrothermal carbonisation (Kruse et al. 2013).

Depending on the temperature and main product formed, three different hydrothermal gasification processes can be distinguished (see also video in ◘ Fig. 19.6):

1. *Aqueous phase reforming*: At relatively low temperatures of around 200 °C and in the presence of a noble metal catalyst, hydrogen is formed from compounds originating from biomass (Davda et al. 2005; Luo et al. 2008). Hydrogen formation as product is thermodynamically possible at this low temperature, but the concentration has to be very low, at around one percent. (Feng et al. 2004; Kruse 2008). A hydrogenation catalyst is necessary. This process can only be applied to biomass-based compounds, but not to raw biomass. Therefore, it can be applied to the aqueous effluent of other processes. The most important advantage of this process is that the catalyst uses the formed hydrogen to hydrogenate the feedstock. The extent to which this consecutive reaction occurs, depends on which noble metal is used as a catalyst (Davda et al. 2005; Huber et al. 2005). In a following step, aromatic compounds that can substitute terephthalic acid can be produced that can be used for PET bottles (Kumula 2011; Serrano-Ruiz et al. 2011).
2. *Near critical catalysed gasification*: Near the critical point, methane is the thermodynamically preferred burnable product. Here, the (nearly) complete gasification and the hydrogenation of carbon monoxide to methane occur in the same reactor. In dry processes, this is not possible because higher temperatures are needed for gasification, which is too high for methane formation. The formation of methane from hydrogen requires hydrogenation catalysts (Ni, Ru, Rd, PT, Pd) for sufficient yields. Only small amounts of methane can be formed via the decarboxylation of acetic acid, without a catalyst. In principle, two versions of near-critical gasification are conducted: Elliott et al. (2006, 2008) prefer subcritical conditions. The advantage is that salts are still soluble, and the risk of plugging is low. In this concept, the biomass is first liquefied and then gasified in a solid-bed reactor filled with the catalyst. A mobile trailer version was constructed and was in use (Elliott 2008). F. Vogel and his group prefers supercritical conditions, which have the advantage of good solubility of organic compounds and gases. To handle the salt deposition, a special gravity separator is used (Brandenberger et al. 2013; Dreher et al. 2013). In near-critical catalysed gasification, the stabilisation of the catalyst is a special challenge (Elliott et al. 2004). In particular, the support of the catalyst must be stable in the highly aggressive aqueous medium. Pure carbon and Al_2O_3 have been found to be sufficiently stable as catalyst support. Elliott et al. (2006) found monoclinic zirconia, rutile titania, and carbon as the best choice for the support. Catalytically active metals are limited to nickel, ruthenium, and rhodium.



◘ **Fig. 19.7** Hydroxymethylfurfural with its two functional groups: it is an aldehyde and an alcohol

3. *Supercritical water gasification*: Biomass with a dry matter content of at least 10% (g/g) and temperatures above 600 °C are required to produce hydrogen in reasonable amounts. Challenges are finding suitable reactor materials and a method of handling salt deposition. The reactor material must be a nickel-based alloy to withstand high temperatures and pressures. However, these materials have varying corrosion stability and are usually expensive and difficult to obtain. As mentioned above, the solubility of salts is poor in supercritical conditions (Kruse 2008, 2009), but alkali salts are necessary to catalyse the water-gas shift reaction: $CO + H_2O \leftrightarrow CO_2 + H_2$. The equilibrium of the reaction lies to the right, with hydrogen as the preferred product due to the high concentration of water, but alkali salts are necessary to reach the equilibrium. Gasification of glucose without alkali, in particular potassium, salts leads to a syngas with high carbon monoxide content. As biomass naturally contains alkali salts, its conversion usually does not require alkali salts to be added. A catalyst is not necessary, but for example carbon is often used to avoid high temperature requirements or to increase the relative gas yield if the biomass has a high dry matter content. Supercritical water gasification is a suitable method to convert agricultural residues, process water, sludges and algae (Kruse 2008, 2009). Larger-scale gasification plants were operational in Karlsruhe/Germany and Hiroshima/Japan. The German plant converted various types of biomass, including corn silage, spent grain and grass on a scale of 100 kg/h slurry (Boukis et al. 2007). In the Japanese plant, the biomass proceeds through a liquefaction reactor before gasification. A special aspect of this plant is that a coal catalyst is fed into the gasification reactor, which can be reused. For details, see also (Kruse 2008, 2009). Such larger plants are important to assess the performance of the process, for example in terms of energy efficiency.

If you are interested in how organic waste in France is processed into renewable gas via hydrothermal gasification, you may refer to the following ▶ Youtube Video by the NaTran group.

19.4 Negative Emissions Technologies

Negative emissions technologies (NET), also known as carbon dioxide removal (CDR) or carbon negative technologies, are strategies or technologies designed to remove carbon dioxide (CO_2) from the atmosphere. These technologies reduce more CO_2 from the atmosphere than their application adds, thereby achieving a net reduction of greenhouse gases (GHG). They are required to achieve carbon neutrality or 'net zero' as they support that the CO_2 released into the atmosphere from human activity is balanced by an at least equivalent amount being removed.

Carbon dioxide removal (CDR) approaches can be either biological, technological or geochemical processes. Examples for *biological CDR approaches*, also known as natural sinks or nature-based solutions (NbS) (see Sect. ▶ 5.5), include afforestation and reforestation, soil carbon sequestration or biochar applications.

- *Afforestation and reforestation (see also* Sect. ▶ 8.5.4*)*
  According to the IPPC (2003), afforestation is the planting of new forests on lands that have not been forested for a period of at least 50 years. Reforestation is the human-induced conversion of non-forested land to forested land through planting on land that was once forested but has been converted to non-forested land. In a simulation study for afforestation by planting jack pine in Canada, Ménard et al. (2023) showed that the system became a net carbon sink after 15 years and remained so until the end of the simulation period. Over a simulation period of 80 years, a cumulative net balance (cumulative fluxes from ecosystem, wood products and displacement effect on markets) of

118.1 t CO_2eq $ha^{-1} \pm 16.8$ and 371.1 t CO_2eq $ha^{-1} \pm 21.4$ with and without harvesting, respectively, was estimated.

- *Soil carbon sequestration*
  Sequestration is the process of increasing the carbon content of a carbon pool other than the atmosphere and thus becoming a carbon 'sink'. Soil carbon sequestration is the accumulation of organic carbon in the soil, which can be induced through adapted land use and soil tillage practices, such as no-till farming, cover cropping, application of organic fertiliser, agroforestry or peatland restoration. In Sect. ▶ 6.11.1 this has been introduced as climate smart farming. According to Zomer et al. (2017), "soils can act as both sources and sinks of carbon, depending upon management, biomass input levels, microclimatic conditions, and bioclimatic change". Substantially more carbon is stored in the world's soils than is present in the atmosphere. The global soil carbon (C) pool to one-meter depth, estimated at 2500 Pg C, of which about 1500 Pg C is soil organic carbon (SOC), is about 3.2 times the size of the atmospheric pool and 4 times that of the biotic pool (Zomer et al. 2017). The soil carbon sequestration potential depends on the initial level of soil carbon, the soil type, climate and management procedures. Tillage accelerates soil carbon loss through exposure of soil organic matter to oxidation by aerobic microorganisms, a process generating CO_2. Thus, "no tillage practices", which were adopted to control soil erosion and to increase soil organic matter in the surface layer by developing a litter layer, also reduces GHG emissions from soil and leads to a net increase of soil carbon (Mehra et al. 2021).
- *Ocean-based Carbon sequestration*
  The conservation and restoring of coastal and marine ecosystems, such as mangroves or salt marshes can sequester carbon. For example, the Global Mangrove Alliance (GMA) strives for a collaboration that seeks to bring together NGOs, governments, scientists, industry, local communities and funders towards a common goal of conserving and restoring mangrove ecosystems.
- *Biochar*
  Biochar is a stable, carbon-rich charcoal that is produced by pyrolyzing biomass (see video in ◘ Fig. 19.4). Incorporated into the soil, it can sequester carbon in the soil for many years and potentially improve soil fertility. Thus, carbon sequestration via biochar could easily be integrated with existing agricultural practices and is thus easily scalable. Biochar properties are depending on the production technology and the nutrient and water absorption capacity of biochar can as well positively as negatively affect plant growth as well as some kind of biochar that come along with contaminations (Jeyasubramanian et al. 2021). On the other hand, biochar can bind these contaminants and prevent them from being available to the crops (Nguyen 2023). The lifetime of char and the duration of carbon storage in the soil is longer than those of other methods, which apply soil amendments. Biochar can last hundreds of years in soils.
- *Bio-based products*
  Every bio-based product, like bioplastic or even more effectively construction materials, are a carbon storage for the life time of the product (Kuittinen et al., 2021).

◘ Figure 19.8 shows how negative carbon emissions can be generated using the example of the perennial biomass crop *Miscanthus*. The starting point for all biological CDR is the fixation of CO_2 and its conversion into carbon products through the process of photosynthesis. If the biomass, e.g., the roots or leaf litter, is incorporated into the soil and remains there, carbon is sequestered. Carbon can also be be bound in bio-based materials for their lifetime, which is of cause much shorter as in the case of biochar. An energetic use of biomass neither add to nor reduce CO_2 from the atmosphere but leads it into circularity.

Technological CDR approaches include technologies for removing CO_2 directly from the exhaust gases of industrial processes and storing it elsewhere, e.g. underground.

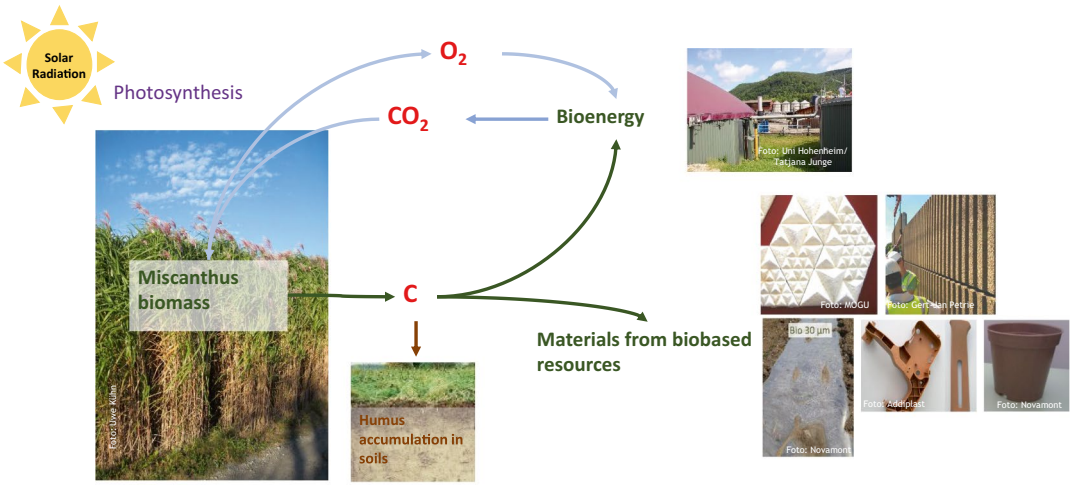


Fig. 19.8 The perennial biomass grass *Miscanthus* captures carbon dioxide (CO_2) through the process of photosynthesis and stores it as carbon in the biomass. Carbon is sequestered in the soil as organic matter (humus) or in bio-based materials. If the biomass is used energetically, here shown by the example of fermentation to biogas, the carbon is released as CO_2 and put back into the atmosphere from where it can be recaptured by biomass. © Iris Lewandowski

- *Direct Air Capture with Carbon Storage (DACCS)*
  DACCS technologies are those that capture CO_2 directly from the air or from exhaust gases of industrial processes and store it elsewhere, e.g. underground. There are two methods for CO_2 capture. For the liquid-based technology, air passes over a chemical solution, which absorbs CO_2. In the solid direct air capture, air passes through a filter that binds CO_2 from the air. However, presently, DACCS is very energy-consuming and can only become negative in CO_2 emissions if renewable energy is used. Due to the low CO_2 concentration of the atmosphere, direct air capture requires more energy and comes along with higher costs than the CO_2 capture from exhaust gases. In a study of Yang et al. (2021), the implementation of CCS combined with industrial facilities resulted in CO_2 avoidance costs of 54–75 €/t CO_2.
- *Bioenergy with Carbon Capture and Storage (BECCS)*
  BEECS describes technologies that combine the use of biomass for energy generation and capture and store CO_2 produced in the process. Meaning bioenergy production, e.g. biofuels or through combustion of biomass in power plants, and immediately capturing the CO_2 and storing it underground. This process combines biological and technological CDR. In a study of Yang et al. (2021) adding CCS to biomass processing generates CO_2 avoidance costs of 40–79 €/t CO_2. The ▶ DRAX Power station in the UK started its first pilot with BECCS to capture CO_2 from biomass combustion in 2019 with one ton CO_2 captured daily. Here, a ▶ post-combustion carbon capture process, where solvents isolate CO_2 from the flue gases produced is applied. The captured CO_2 is pressurised and turned into a liquid-like substance so it can then be ▶ transported by pipeline. The captured CO_2 is injected into naturally occurring porous rock formations or saline aquifers (Drax Group 2021). There is a fully operational BEECS at commercial scale in the US, capturing 1 million tons of CO_2 yearly at a facility which produces ethanol from corn. In this ▶ Illinois Industrial Carbon Capture and Storage project the CO_2 capturing costs can be as low as 25 USD/ton CO_2. (Budinis 2020).

Lask et al. (2021) assessed the GHG balance of a BECCS implemented in ethanol production from miscanthus biomass in a fictitious biorefinery project. The modelled temporary biological carbon storage assuming that all carbon stored in the belowground biomass is released after the cultivation period. Indefinite biological carbon storage assumes that all carbon remains indefinitely in the soil. For this study, three yield levels of miscanthus are compared: 19, 22 and 25 t dry matter per hectare. In the conservative assumption of temporary storage of the biologically captured CO_2, emission reductions of more than 104% relative to the fossil comparator and thus net-negative emissions are achieved. The assumption of indefinite biological carbon storage even results in higher emission savings of 138% (Lask et al. 2021).

Geochemical CDR approaches include measures such as enhanced weathering and increasing ocean productivity:

- *Enhanced weathering*
  Enhanced weathering is a technique that aims at speeding up natural weathering processes that absorb CO_2. In this process, rocks break down due to natural processes such as wind or rain and release charged particles, which react with and bind CO_2 in rainwater and air. Technically, this can be done by spreading finely ground silicate rocks or carbonate minerals on land or onto the sea surface to chemically react with CO_2 in the atmosphere, forming stable carbonates that store carbon (Bach et al. 2019). The company Vesta adds a carbon-removing sand made of the natural mineral olivine to coastal systems. This nature-based climate strategy reduces ocean acidity and removes carbon dioxide permanently. Heirloom Carbon Technologies also develops technologies to accelerate the natural weathering process of minerals to capture CO_2 using limestone.
- *Increasing ocean productivity*
  Techniques such as ocean fertilisation with iron or other nutrients, which stimulate the growth of phytoplankton that absorb CO_2 or using seaweed farms, can capture carbon.

The company Running Tide, based in Portland, Maine, offers credits to customers from two pathways of carbon removal: Ocean alkalinity enhancement and biomass sinking. It plans to set tens of thousands of tiny floating kelp farms adrift in the North Atlantic. The hope is that the fast-growing macroalgae will eventually sink to the ocean floor, storing away thousands of tons of carbon dioxide in the process. Seafields Solutions is a UK-based aquaculture business that aims to cultivate sargassum seaweed in the open ocean to absorb CO_2 and then sink it to the deep sea for long-term storage.

Do you want to learn more about the valorisation of residual streams in decentralised biorefineries? Take a look at Supplementary Material 19.1, a video from our MOOC "Concepts of Sustainable Bioeconomy" (2021).

Questions

1. What is the role of water in "wet" conversion processes?
2. Name the products of hydrothermal gasification processes.
3. What is the goal of applying negative emission technologies (NET)

Answers

1. In wet processes, such as hydrothermal processes, 'wet' biomass is converted without drying and the water in the biomass becomes the reaction medium.
2. Depending on the temperature and main product formed, three different hydrothermal gasification processes can be distinguished:
   (a) *Aqueous phase reforming* produces hydrogen
   (b) *Near critical catalysed gasification,* where methane is the thermodynamically preferred burnable product
   (c) *Supercritical water gasification* producing syngas with high carbon monoxide content.
3. Negative emissions technologies (NET), also known as carbon dioxide removal

(CDR) or carbon negative technologies, are applied to remove carbon dioxide (CO_2) from the atmosphere. With these technologies, more CO_2 shall be removed from the atmosphere than their application adds. The aim and effect is thereby achieving a net reduction of greenhouse gases (GHG).

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Food Processing

Myriam Loeffler and Jörg Hinrichs



Fig 20.0 Food processing. (© Universität Hohenheim/Corinna Schmid) (► https://doi.org/10.1007/000-hv1)

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Food science and technology is the science that deals with the physical, biological and chemical processes relevant to the processing of food and food ingredients. The goal is to research, develop and optimise technical procedures based on natural and engineering sciences as well as socioeconomic factors in order to provide high-quality and safe food for human consumption. Food processing refers to the conversion/transformation of raw materials to a safe food product. This chapter introduces the physical, chemical and biological unit operations typically used in food processing to ensure food safety and quality. The influence of intrinsic as well as extrinsic parameters on microbial growth behaviour are highlighted and examples of important factors that need to be considered during food processing are introduced (water activity, enzyme activity, lipid oxidation). At the end of the chapter, also strategies for new product developments are presented.

Learning Objectives

After studying this chapter, you will…

- …be able to describe the factors that influence microbial growth (see ► Sect. 20.3).
- …be able to explain basic processes used in food processing and drivers of technical food processing (see ► Sects. 20.2, 20.4, 20.5, and 20.6).
- …be able to discuss aspects of importance for the development of new food products (see ► Sects. 20.7 and 20.8).

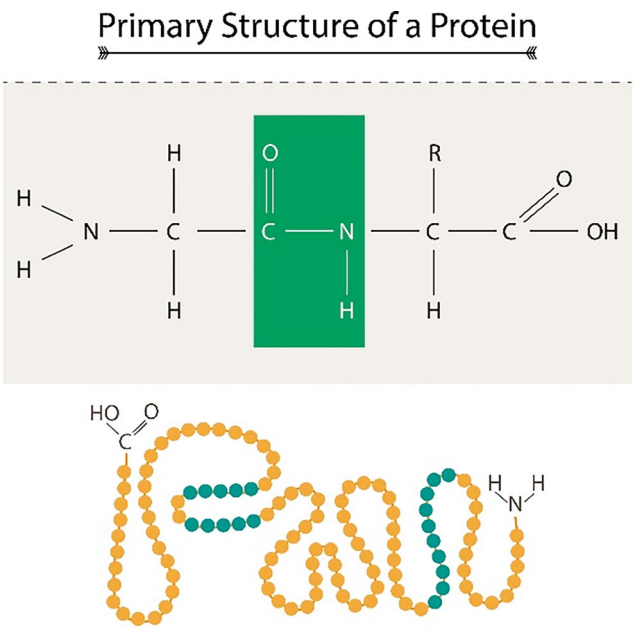
20.1 Food and Food Ingredients

The term *'food'* encompasses substances and products consumed by humans primarily for nutrition and/or pleasure. This broad definition extends beyond conventional perceptions of food and includes, for instance:

- Alcoholic beverages
- Food ingredients such as salt and spices
- Food additives such as thickeners
- Food supplements such as minerals and vitamin preparations

Major food ingredients (the big five) are:

- Water
- Proteins (■ Fig. 20.1)
- Fat (■ Fig. 20.2)



■ **Fig. 20.1** The primary structure of a protein refers to the linear sequence of amino acids linked by peptide bonds. Shown here is an example of a peptide bond formed between glycine (left) and another amino acid (rest indicated by R). The bottom section shows a simplified representation of a polypeptide chain, indicating both the C-terminus and the N-terminus

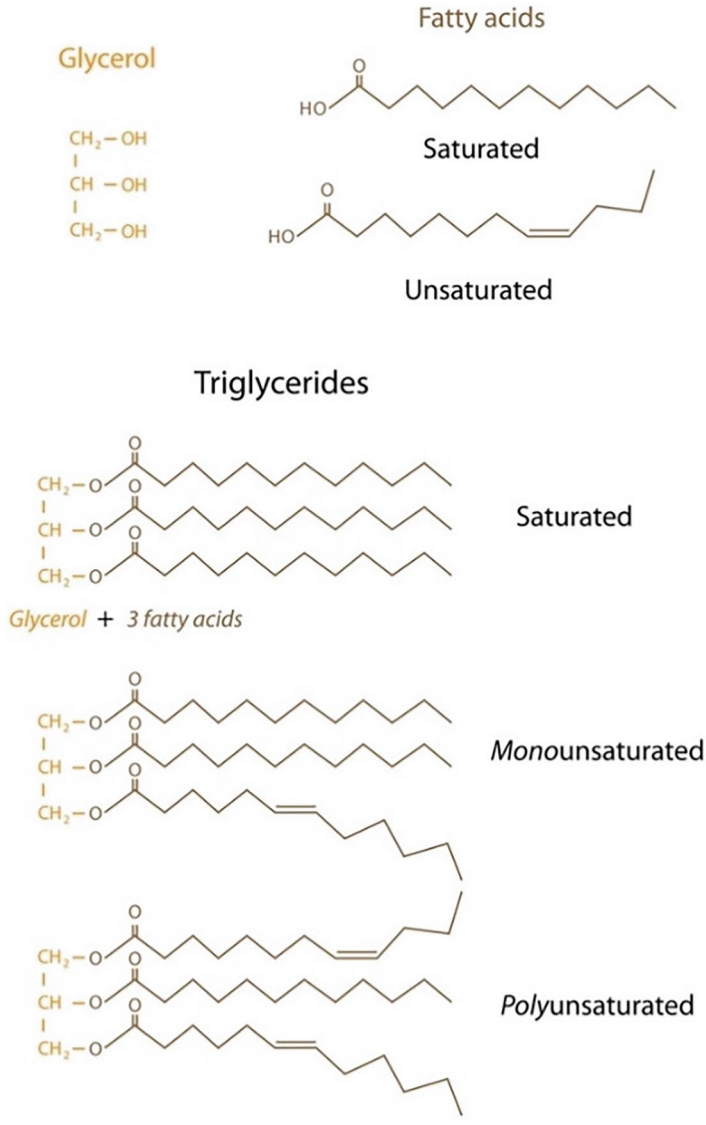


Fig. 20.2 Structure of glycerol, saturated and unsaturated fatty acids, and triglycerides

– Carbohydrates (e.g. the monosaccharide glucose, disaccharide lactose, and the polysaccharides cellulose and starch)
– Minerals (e.g. calcium, iron, magnesium, zinc)

Minor components/other micronutrients are:
– Vitamins (fat- or water-soluble)
– Other functional components

For more information on food ingredients, particularly proteins please refer to ▶ Chap. 21.

20.2 Unit Operations of Food Processing

For consumers, food is not just a source of satiety (energy) and essential micronutrients; it also delivers a pleasurable experience through its aroma, taste, colour and texture. Moreover, ritual functions (e.g. the Eucharist) and prohibitions (e.g. Jewish food regulations) are linked to food and food consumption. Nowadays, quite a

few of these prohibitions can be explained and understood by looking at former climatic and hygienic conditions and the related diseases. For instance, it is well known that beans should not be consumed without processing. Raw beans contain a toxic protein (phasin), which has to be denatured prior to consumption by heating or pickling to prevent intestinal colic. Thus, knowledge of the cultivation, storage, preservation and processing of food was and still is of great importance. In this context, food processing describes the conversion/transformation of raw material to a safe food product.

Today, there is a variety of possibilities (e.g. unit operations) to convert and hence process plant and animal raw materials to semi-finished goods (e.g. flour), ready-to-eat end products (e.g. bread), and convenience food, including special diets. A distinction has to be made between physical, biological and chemical methods used for raw material and food processing. Depending on the requirements, these techniques may be applied individually, in a particular order, or in combination. Table 20.1 gives an overview of unit operations used in food processing. Most of these techniques such as milling, drying, fermentation and thermal processing, were developed a long time ago and then adapted to different food matrices. More recent technological innovations include irradiation, high-pressure processing (HPP), pulsed electric fields (PEF) or membrane filtration, the latter being widely used in dairy- and beverage processing to achieve separation with lower energy requirements.

Table 20.1 Examples of food processing objectives classified by main principle and listing of unit operations applied

Main principle	Objective	Unit operation
Physical	Removal of dirt and unwanted components	Washing, sieving, peeling
	Crushing	Cutting, grinding, crushing
	Enrichment of certain components	Pressing, separating, filtering, distilling, extracting, evaporation, drying, crystallisation
	Texture alteration	Kneading, dispersing, emulsifying, foaming
	Shelf life	Heating, cooling, freezing, drying, microwave heating, irradiation, high pressure
	Destroying interfering or toxic substances	Blanching, cooking
	Improved digestibility, formation of aromas, browning	Heating, frying, cooking, steaming
Biological	Raw material transformation → taste, smell, texture	Fermentation, fermentative acidification, enzymatic reactions
	Shelf life	Fermentation (acidification, bacteriocin production)
Chemical/ biochemical	Taste and texture	Addition of salt or/and sugar
	Shelf life	Addition of salt, sugar or acid, smoking, addition of preservatives
	Destroying/inactivation of interfering or toxic substances	Acidification, heating
	Optical appearance	Addition of colourants

With the beginning of industrialisation in the second half of the eighteenth century, major technical advances were made in crop and plant cultivation, food processing and packaging. For instance, research findings of Justus Liebig led to an increase in agricultural production of about 90% between 1873 and 1913. The use of fertilisers, scientifically based animal breeding and the initial mechanisation of agriculture allowed more and more people to be supplied with food. At the same time, new methods of preservation and packaging were developed (e.g. 1804, sterilisation of milk) to extend storage time and improve food transportation, leading to a marked increase in small-scale and large-scale operating companies in Europe and beyond.

20.3 Food Quality, Shelf Life and Food Safety—Drivers of Technical Food Processing

An important requirement for the storage and trade of food and food ingredients is that they either retain their specific properties (best case) or undergo only minor physico-chemical and/or microbial changes over a longer period, thus guaranteeing food quality and safety.

In this context, "safe" refers to food products that are free from harmful levels of pathogens, toxins, or other hazardous substances that could pose a risk to human health at the time of consumption. Many of the physical, biological and chemical methods listed in ◘ Table 20.1 are used to prolong shelf life, but they may vary depending on the product. In the past, food products were often preserved by reducing water activity (▶ Sect. 20.5) or through fermentation. For instance, foods already traded in antiquity included dry products such as salt, sugar, cereals, dried meat and spices, or fermented products such as wine or vinegar, as well as salt-conserved products including fish (e.g. salt cod), meat and cheese. Therefore, salt became an important commodity a long time ago, since it was essential for food preservation and seasoning.

20.3.1 Factors Affecting Microbial Growth

As our foods are of animal and/or plant origin, it is important to consider the raw material and product characteristics that may influence microbial growth during harvesting, food processing and (short- /long-term) storage.

20.3.1.1 Intrinsic Parameters

1. pH

Microorganisms can be classified according to the minimum, optimum (best growth requirements) and maximum pH value at which they can grow. For certain food products, knowing the pH is of vital importance. For instance, yoghurt (pH 4.3–4.7) and fruit juices (pH 3.5–3.8) have a very low pH and are therefore mainly spoiled by yeasts and moulds, while emulsified sausages have higher pH values (5.9–6.2) and are very prone to contamination with food spoilage (e.g. pseudomonads) or food poisoning bacteria (e.g. *Listeria monocytogenes*).

2. Moisture Content

The preservation of foods by drying is achieved by the removal or binding of moisture, without which microorganisms are not able to grow. See also water activity in ▶ Sect. 20.5.

3. Oxidation-Reduction Potential (ORP, Eh)

The oxidation-reduction potential is a measure of a food system's capacity to accept or donate electrons, reflecting the balance between oxidizing agents (electron acceptors) and reducing agents (electron donors) within the food matrix. Processing operations that, e.g. increase the surface area of a food product, such as meat grinding, expose it to more oxygen and thereby raise the *Eh*. Conversely, modified atmosphere packaging or vacuum packaging reduces the *Eh* by limiting oxygen exposure. Aerobic microorganisms, such as *Pseudomonas spp.*, require positive *Eh* values for growth, whereas anaerobes such as *Clos-*

tridium botulinum require negative *Eh* values. However, it should be noted that many bacteria are facultative anaerobes and can hence grow under either aerobic or anaerobic conditions.

4. Nutrient Content

Nutrient requirements for microbial growth include water (solvent for nutrients; facilitates metabolic processes), an energy source (e.g. sucrose or glucose), a nitrogen source (e.g. proteins or amino acids), vitamins and other growth factors, as well as minerals (▶ Sect. 20.1). The requirements vary by species and strain level. Many Gram-positive bacteria are known to have more complex nutrient requirements compared to Gram-negative bacteria.

5. Antimicrobial Constituents

Antimicrobial constituents that are naturally present in foods include lysozyme (found in eggs and milk), the lactoperoxidase system (present in bovine milk), or essential oils (derived from natural sources such as herbs, spices, fruits and other plants).

20.3.1.2 Extrinsic Parameters

Extrinsic parameters also play a crucial role in microbial growth.

1. Temperature

This includes processing temperatures (e.g. pasteurisation, sterilisation) and storage temperature (e.g. cold storage).

Here it should be noted that microorganisms could also be classified according to their growth temperatures:

- Psychrotrophs (optimum: 20–30 °C; can grow well at or below 7 °C; e.g. *Pseudomonas aeruginosa*)
- Mesophiles (optimum: 30–40 °C; grow well above 20 °C and below 45 °C e.g. *Escherichia coli* O157:H7)
- Thermophiles (optimum: 55–65 °C; grow well at and above 45 °C e.g. *Streptococcus thermophilus*)

2. Other Parameters

Other parameters that should be considered are relative humidity of the environment and the presence of gases (e.g. CO_2), the application/presence of other microorganisms that produce e.g. substances that are inhibitory or even lethal to other microorganisms (e.g. bacteriocins, organic acids) and/or the use of preservatives.

Note that generally, a ***hurdle concept*** is used in food production, referring to the strategic combination of multiple preservation methods (or "hurdles") to inhibit microbial growth and ensure food safety while maintaining high product quality. These hurdles may include parameters such as temperature, pH, water activity, redox potential and/or the use of preservatives, acting together to create a stable and safe food product.

20.4 Special Features of the Large-Scale Processing of Food

The general principles and requirements of large-scale food processing do not differ from homemade, small-scale processing – they usually involve the raw materials, a recipe and the necessary equipment. In all cases, the end product is expected to be safe and to have a high sensory quality with regard to taste and aroma, colour, and texture. Some products may also have additional nutritional or functional health requirements. In food processing companies, all these requirements are the responsibility of the manufacturer and once products are on the market, they are subjected to state quality standard monitoring.

In general, large-scale food production is characterised by a higher degree of automation. In addition, a "higher" safety level is required, since the semi-finished or final products are often marketed over long distances, which in turn requires a longer shelf life and appropriate packaging. In cases where quality

deficiency or damage is identified, the recall of large-scale products is much more difficult than for locally marketed products.

20.4.1 Raw Materials

The following factors are of particular importance for food production:

- The bulk of raw materials used are of natural plant or animal origin. They have a great variability with respect to composition, autochthonous microorganism flora and processing properties.
- The availability of many raw materials (e.g. fruits, sugar beet…) is limited by seasonality.
- Plant raw materials (e.g. coffee, soy, hops) are often only cultivated in certain regions, leading to long transport distances.
- Raw materials are not always available in unlimited supply and their storage is only possible for a limited period of time.
- High price fluctuations are possible.

Today, other socioeconomic aspects related to the selection of raw materials are taken into account. These are often described by terms such as "resource-conserving", "organic", "eco", "GMO-free", "climate-neutral", and "fair trade".

20.4.2 Processing of Raw Materials

In the next step, the raw materials are converted into standardised *(quality attributes and/or functional properties)* products through various unit operations. For this reason, the chemical, biological and physical properties of the raw materials and also their behaviour during processing have to be taken into account. The technology-structure-function relationship behind the processing of raw materials (e.g. sugar beet, milk) into foodstuffs (sugar cubes, processed cheese) is illustrated in Fig. 20.3. In the Figure, "technology" includes the substances and ingredients used, their concentration and composition, as well as the basic operation(s) applied (Table 20.1). The desired functionality of the product is achieved through the choice of process parameters (e.g. pressure, temperature and pH). The structure of the final product (e.g. sugar cubes: small crystals in the form of a cube of defined edge length, white, solid) is predominantly influenced by the technology used. In turn, the structure provides the basis for the functionality of certain food products (e.g. sugar cubes: dissolve rapidly in hot liquids; desired sweetness).

For the same raw material, even small changes in the process parameters of basic operations, the use of other machines/equipment, or a change in the order of the unit operations can influence the structure and thus also the functionality of the end product. This may or may not be advantageous for the application in question.

Nowadays, food product properties are divided into techno-functionality (e.g. attributes related to the role of ingredients/processing in achieving specific functions such as shelf life, texture, foam stability, emulsion formation, etc.) and bio-functionality (e.g. nutritional value or health-promoting effects).

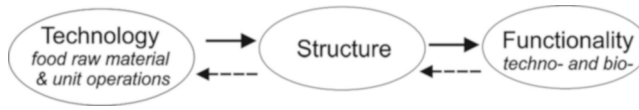


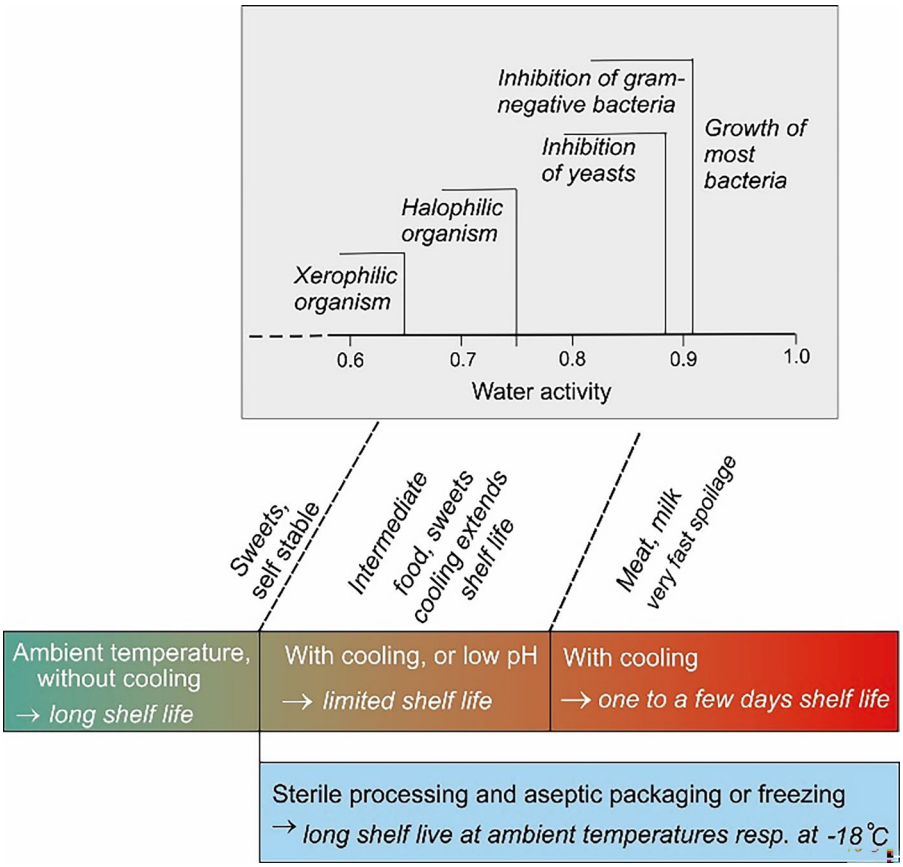
Fig. 20.3 Technology–structure–function relationship for the processing of food as well as the development of new food products

20.5 Toolbox Used in Food Processing

Food science and technology deals with the physical, biological and chemical processes relevant to the processing of food and food ingredients. The goal is to research, develop and optimise technical procedures based on natural and engineering sciences as well as on socioeconomic factors in order to provide high-quality and safe food for human nutrition. As it is not possible to give an in-depth account of all the factors that need to be taken into account, a few selected important examples are presented here.

20.5.1 Water Activity

As shown in ◘ Table 20.1, various unit operations can be used, for which a wide range of machines and equipment is available. The physical properties (e.g. liquid/solid), the chemical composition, and, in particular, the water content of the raw materials to be processed are of high importance. However, it is freely available water rather than the total water content that is crucial for appropriate processing. ◘ Figure 20.4 shows the intensity of various reactions depending on the water activity. The water activity (a_w) value is calculated as the water vapour pressure of the raw



◘ **Fig. 20.4** Potential of microorganisms to grow on food depending on water activity (above). Potential shelf life of food and processed food under certain storage conditions (below)

Table 20.2 Water activity of various food raw materials and food products

Water activity	Food raw material, food products
≥0.98	Fish, meat, milk, egg, vegetables, juices, fruit, yoghurt, fresh cheese, soft cheese
0.95–0.97	Sausages, semi-hard and hard cheese
0.86–0.92	Raw sausage (salami), raw ham, parmesan
0.80–0.90	Jam, cakes, bread, syrup, sweetened condensed milk, flour, rice, ketchup
0.70–0.80	Soups, marzipan, dry fruit cakes, dried plums, jam of higher concentration
0.60–0.70	Honey, nougat, raisins, muesli, nuts, confectionery, dried fruit
0.5	Pasta, spices
0.4	Egg powder
0.3	Cookies
0.2	Milk powder

material/foodstuff divided by the vapour pressure of pure water at the same temperature. Substances of low molecular mass, such as salts or sugars, interact with water molecules by water molecules and can thus reduce the water vapour pressure above the food and therefore also the a_w value.

If the water activity is very close to 1 (Table 20.2), the product is very prone to microbial spoilage, especially if cold storage is insufficient. The unit operations drying and salt addition (Table 20.1) can reduce the a_w value (Table 20.2). Freezing also reduces the mobility of water, preventing microorganisms from growing and reducing the rate of chemical reactions. Consequently, this process is now widely used to protect raw materials, semi-finished products and finished products from spoilage and to preserve vitamins, colour and texture. Many other reactions that also affect food quality, such as lipid oxidation, are directly related to water activity, as demonstrated in Figure 20.5.

20.5.2 Enzyme Activity, Lipid Oxidation

As can be seen from Figure 20.5, enzymatic reactions can be expected until a very low water activity of 0.4 is reached. Therefore, raw materials must be treated in such a way that existing enzyme activities do not lead to undesired changes in sensory properties, colour or texture. One way to prevent enzyme activity and to kill microorganisms at the same time is through heating. However, heating can lead to non-enzymatic browning by the Maillard reaction. The reaction takes place between proteins and sugars and may cause desired (caramel, bread, malt beer) or undesired (juices, milk powder) effects depending on the characteristics of the food product.

It is interesting to note that the oxidation of lipids (fats) is lowest at a water activity of 0.2 (minimum) and more pronounced in products with either a lower ($a_w < 0.2$) or higher water activity ($a_w > 0.2$). Thus, fat-containing egg powder and products with many unsaturated fatty acids can only be protected from lipid oxidation by appropriate packaging materials, a protective modified atmosphere without oxygen, or antioxidants. Figure 20.5 and Table 20.2 provide relevant information on some of the unit operations mentioned above, necessary for the fulfilment of requirements regarding shelf life, safety and preservation of the sensory properties of a food product.

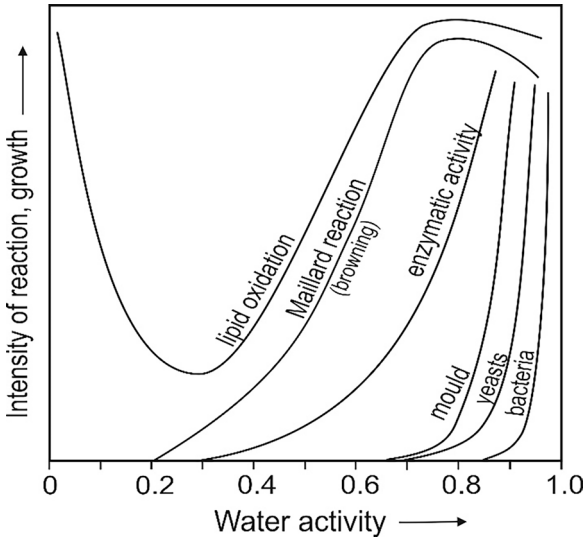


Fig. 20.5 Qualitative description of the intensity of chemical and biochemical reactions, as well as microbial growth, depending on water activity

20.5.3 Thermal Treatment & Pasteurisation

One of the most important unit operations is the thermal treatment of food (Table 20.1). Thermal treatments enhance food safety by killing or inactivating pathogenic germs and viruses, while also extending shelf life by eliminating spoilage organisms and inactivating both enzymes already present in the product and microbial enzymes. It should be noted that microbial endospores are particularly heat-resistant. However, (intensive) heat treatments may also destroy thermolabile vitamins and accelerate chemical reactions, including the Maillard reaction mentioned above.

▶ Milk Production

Raw milk is an easily perishable foodstuff since it has a near-neutral pH and a water activity close to 1 (Table 20.2). It was recognised as early as the nineteenth century that raw milk can contain pathogenic microorganisms and is capable of transmitting diseases to humans. It is therefore a legal requirement that raw milk obtained directly from the producer has to be boiled before consumption. However, boiling milk at 100 °C is not a very gentle treatment and can have a negative effect on its components. Given that *Mycobacterium tuberculosis* (discovered by Robert Koch in 1882, disease: tuberculosis) is one of the most thermostable pathogens in raw milk it was used to define heating requirements for the pasteurisation of milk. Figure 20.6 gives a summary of heat-based methods for the inactivation of pathogenic organisms. Short-time pasteurisation at 72–75 °C for 15–30 s provides a safe product with a shelf life of max. 10 days when stored at <8 °C. A longer shelf life is not possible because bacterial spores, which are highly resistant and help bacteria to survive extreme conditions, are not fully inactivated during pasteurisation. ◀

20.5.4 Sterilisation

Sterilisation is carried out following a traditional process developed by Apert in 1804. The milk is filled into cans or bottles, sealed and then heated in an autoclave (Fig. 20.6). An autoclave is a pressure vessel in which temperatures of about 120 °C are reached using overpressure. If this temperature is maintained for about 20–30 min, mesophilic and thermophilic bacterial spores are inactivated. Sterilised milk has a shelf life of 1 year and can be stored at room temperature. However, the treatment is not very gentle. The heating area for sterile milk (Fig. 20.6) is above the

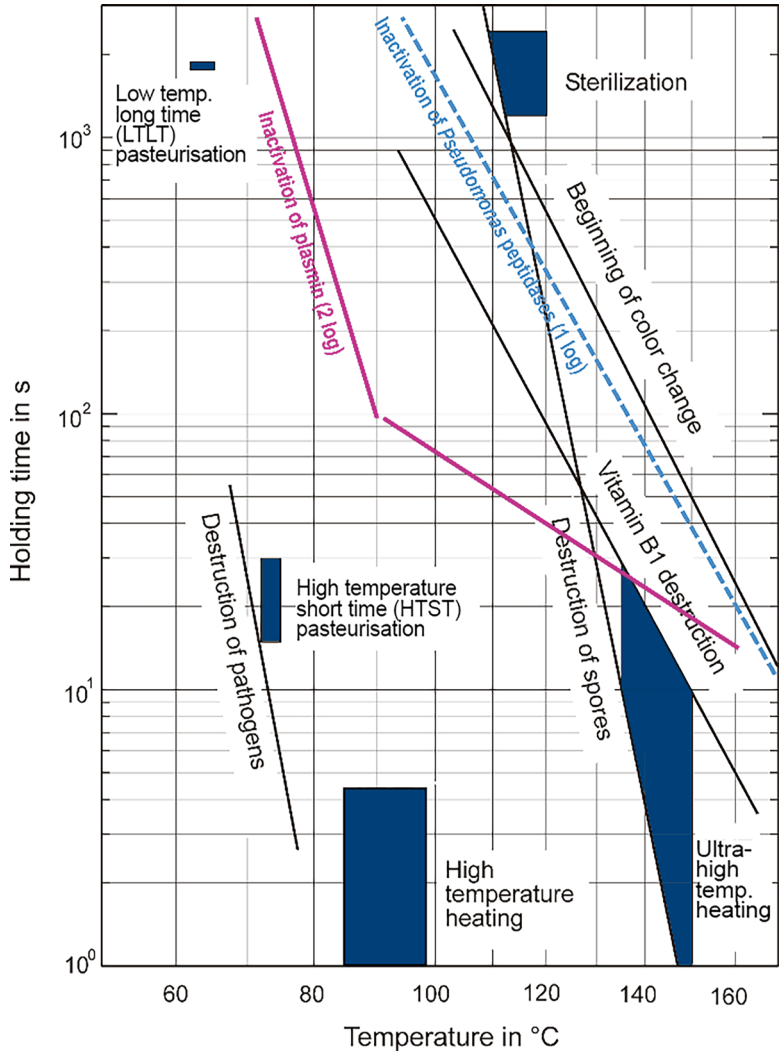


Fig. 20.6 Kinetics of some example reactions associated with milk heating. (Based on Stoeckel et al. (2016))

line for visible browning (Maillard reaction) and above the line that marks lysine (an essential amino acid) and vitamin B1 (thiamine) losses. It was not until 1952 that the process of ultra-high-temperature heating (Uperization) was developed by Alpura (Switzerland). In this process, the milk is heated to about 145 °C in just a few seconds, kept hot for a few seconds, and then rapidly cooled down again. The heating area used for UHT milk (Fig. 20.6) lies below the line for lysine and vitamin B1 losses but above the spore inactivation line. UHT milk is thus comparable to sterilised milk with regard to shelf life, but the method is more favourable with regard to the components.

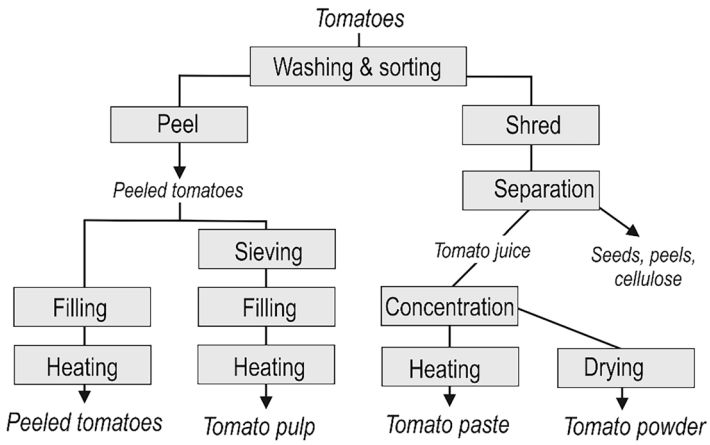
20.6 Complexity of the Technologies Needed to Produce Different End Products from the Same Raw Material

▶ Products from Tomatoes

All final products mentioned in ◘ Figure 20.7 are semi-finished products (e.g. ketchup, sauces, soup), which are used in households as products or as ingredients for food preparation. The raw material 'tomato' has to be selected and controlled in terms of variety, taste, colour, texture and maturity, with the functionality of the end product in mind. Immediately after delivery, the tomatoes are washed, sorted, and then further processed using various operations and machines. For instance, after peeling, the tomatoes are filled directly into cans, to which tomato concentrate and, in some cases, also salt are added for better preservation of the tomatoes' structure for subsequent sterilisation in the autoclave at 95 °C. Alternatively, peeled tomatoes are passed through sieves (pulp) or chopped (cubes) and then canned and sterilised. As the sterilisation of larger containers (300–1500 kg) is not possible (heating and cooling would take hours and affect the quality of colour, texture, taste, etc.), the products are continuously heated in heat exchangers, kept hot for a short, defined period of time and then rapidly cooled. The products are then filled under aseptic conditions into previously sterilised containers. The production of tomato paste and powder requires further process steps including separation, concentration and/or drying. ◀

Excursus 20.1: Process Indicated Diagrams

Process indicated diagrams are usually used in which the unit operations are named as process steps and delimited by a framework of substances (raw materials and additives, ingredients, intermediate products and end products). Just as the process parameters, the chemical, physical and (micro) biological properties of the substances that are important for the production process are given as "setpoints". During processing, the substances are regularly analysed and the process parameters then automatically logged ("actual value"). On the one hand, this is part of the quality assurance to meet the requirements requested by law. On the other hand, this guarantees a final product with most widely standardised functional properties.



◘ **Fig. 20.7** Combination of process steps (boxes = unit operations) for the production of various tomato products for a range of applications

20.6.1 Energy Use, Water Consumption, and Valorisation Potentials

Technological developments not only enable the manufacture of products with a defined functionality and safety but also promote economical and more sustainable use of water and energy resources. For example, the processing of foodstuffs requires an average of around 1–2 kg of water per kg of processed product, including the water required for cleaning operations. In many cases, water removed from the product during concentration or other processes is recycled within the production system. Moreover, closed-loop water systems have further minimised water consumption in recent years. Energy consumption in food processing has also been markedly reduced due to the product-dependent adoption of energy-efficient technologies, such as HPP, infrared heating, by the introduction of high-temperature heat pumps instead of hot water/steam heating and/or waste heat recovery systems. Organic waste is also utilised in biogas plants to generate heat, electricity, or fuel, contributing to a circular bioeconomy. Additionally, many facilities now integrate renewable energy sources like solar, wind or biogas to further decrease reliance on fossil fuels. Moreover, efforts to reduce food waste and valorise side streams from food processing have resulted in the production of high-value by-products, including dietary fibres, protein concentrates or isolates, and bioactive compounds. These trends are also reflected in the packaging companies, where, e.g. materials based on biopolymers are being developed and investigated.

20.7 Strategies/Approaches for New Product Developments

Innovative companies generally launch a new product idea (Fig. 20.8) following existing trends or resetting trends by responding to changing consumer habits, social conditions (e.g. full-day child care) or trade demands. Once the (functional) product characteristics have been specified and the target consumer

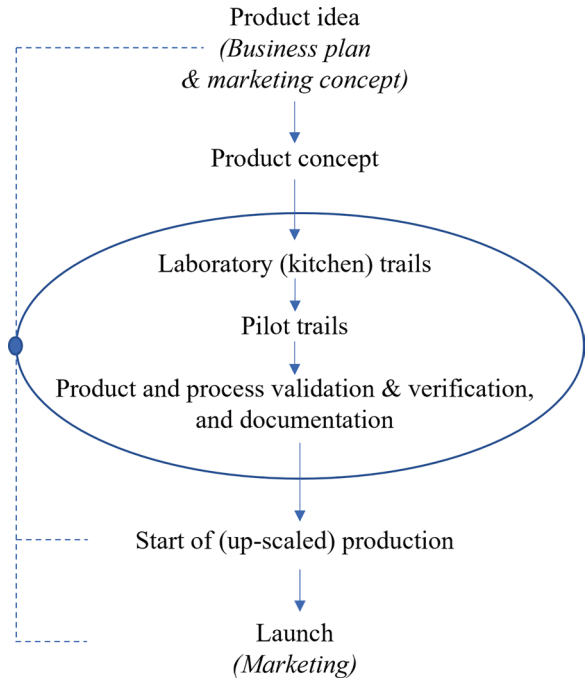


Fig. 20.8 From the idea to the new food product

groups identified, a marketing and business concept is required. This should include an analysis of the market potential in terms of sales volume and pricing.

The actual product development process typically starts with (preliminary) experiments on a laboratory scale, followed by pilot plant trials to validate the technology used to manufacture a product with the desired structure and functionality. Additional experiments are conducted to assess shelf life under various conditions.

Translating a product idea into practice involves addressing numerous critical aspects. These include the selection of raw materials, additives (there is a growing interest towards "Clean Label") and other ingredients (and their suppliers), establishing additional specifications where needed, and ensuring adherence to existing specifications, choosing appropriate processing technologies and conditions, conducting a risk analysis (HACCP), and designing and/or validating test procedures for both the materials and functional properties. Furthermore, appropriate packaging and storage concepts, as well as shelf-life considerations, are essential in this context.

The unit operations required producing a safe product with certain functionalities as well as their sequence need to be defined, and critical control points determined (HACCP). In this context, a clear process flow chart accompanied by a detailed process description should be developed and (re-)validated.

These steps are re-evaluated and repeated multiple times (Fig. 20.8) before transitioning to scaled-up production. Technical and legal requirements for production facilities and product declarations and labelling must also be carefully considered.

Once all these steps have been completed and the product documentation is finalised, the "official" production and supply to retailers can begin. After the new product is launched and established on the market, is it important to monitor its market success and to further optimise the recipe to maintain or improve quality and meet evolving consumer expectations. Only about one idea out of 100 will be successful in the long run.

20.8 Concluding Remarks

The technical processing of food should be seen as a continuous process of development that usually follows consumer demands. New technologies enable, for example, the decaffeination of coffee, the dealcoholisation of beer, lactose reduction in dairy products, reduction of allergens and the production of fat-reduced foods that still taste good. Additionally, technical food production allows the supply of a wide variety of high-quality food products at reasonable prices. Without technically processed products with a long shelf life, the supply of megacities could no longer be guaranteed, even in developing countries.

A new focus is the valorisation of product waste and side streams, biorefinery and the use of "new" resources (depending on the country). Current research studies therefore have a strong focus on, for example, alternative protein resources (e.g. from microalgae, insects and plants) but also on techniques that help to monitor the temperature history of food products during transportation and storage (e.g. time temperature indicators).

Questions

1. What is meant by the term a_w-value/water activity?
2. What are differences between pasteurisation and sterilisation of milk regarding aspects such as shelf life, storage conditions, nutrient value and convenience.
3. Discuss traditional homemade and large-scale processing regarding present demands of growing cities and world population, food safety and food security.
4. Demonstrate the main steps to bring a new product idea to the market. Discuss processing requirements needed to produce a certain product and consider storage temperature as well as shelf life.

Answers

1. The water activity (a_w) value represents the ratio of the water vapour pressure of the raw material/foodstuff divided by the vapour pressure of pure water at the same temperature. It indicates how prone a certain raw material/foodstuff is to spoilage and whether measures of preservation need to be taken.
2. The differences between pasteurisation and sterilisation regarding shelf life, storage conditions, nutrient value, and convenience are as follows:
   - Shelf Life:
     Pasteurisation: Provides a shorter shelf life, typically up to 10 days when stored at temperatures below 8°C.
     Sterilisation: Results in a much longer shelf life, typically up to 1 year, and can be stored at room temperature.
   - Storage Conditions:
     Pasteurisation: Requires refrigeration (below 8°C) to maintain product safety and quality.
     Sterilisation: Can be stored at room temperature without the need for refrigeration.
   - Nutrient Value:
     Pasteurisation: Generally, causes minimal nutrient loss, though it may reduce some thermolabile vitamins and enzymes. The process is gentler compared to sterilisation.
     Sterilisation: More severe heat treatment that can result in greater nutrient losses, particularly in vitamins like B1 (thiamine) and essential amino acids like lysine. This process is harsher and can cause browning (Maillard reaction).
   - Convenience:
     Pasteurisation: Requires careful storage under refrigeration, limiting its convenience compared to sterilised products.
     Sterilisation: Offers greater convenience, as it does not require refrigeration and has a long shelf life, making it more suitable for situations where refrigeration may not be available.
3. Traditional homemade and large-scale food processing differ significantly in their ability to address the demands of growing cities, food safety and global food security. Homemade processing is typically small-scale and relies on local, seasonal raw materials, using simple techniques like drying, fermenting, or pickling. While this approach is resource-efficient and sustainable, it often results in products with limited shelf life and inconsistent safety and quality, as outcomes depend largely on individual expertise. In contrast, large-scale processing is designed to meet global and urban demands through automation and advanced technologies. Methods such as pasteurisation, sterilisation, and high-pressure processing ensure uniformity, extend shelf life, and enhance food safety. Food processing also overcomes seasonal and regional limitations by sourcing ingredients globally and employing sophisticated preservation techniques. This scalability is vital for ensuring food security in densely populated cities and for feeding a growing world population. Moreover, food production incorporates sustainability initiatives, such as energy-efficient technologies, water recycling, and waste valorisation, to mitigate environmental impact. Regulatory oversight ensures compliance with safety standards and traceability, enabling better control over food quality and recall management. While traditional processing is rooted in simplicity and sustainability, large-scale methods are indispensable for addressing the complex challenges of urbanisation and global food supply.
4. Bringing a new product idea to the market involves several critical steps, each addressing the functional, technical and market requirements of the product. The key stages include:
   (a) Idea Generation and Market Research

The process begins with identifying trends, consumer demands or gaps in the market, such as the need for healthier, convenient or innovative foods. Once an idea is formed, target consumer groups are identified, and a marketing and business plan is developed, including sales potential and pricing analysis.

(b) Product Development

Experiments are first conducted on a laboratory scale to test the feasibility of the product concept. Functional characteristics, such as nutritional value, taste, texture, and shelf life, are evaluated. This stage may involve adjustments to recipes or ingredients to meet functional or "clean label" requirements.

(c) Pilot Plant Trials

After successful lab experiments, the process is scaled up to a pilot plant to validate production technologies. Unit operations such as mixing, heating, drying, or fermenting are optimised for consistency and efficiency, considering the technical and economic feasibility.

(d) Risk Analysis and Validation

A hazard analysis (HACCP) is conducted to identify potential risks and ensure food safety. Tests for storage conditions and shelf life are carried out, simulating real-world conditions to determine appropriate packaging and storage solutions.

(e) Processing and Storage Requirements

Processing techniques depend on the product. For example, thermal treatments like pasteurisation or sterilisation are used to extend shelf life, while cold-chain storage is necessary for perishable goods like yogurt. Non-thermal methods, such as high-pressure processing, may be employed for sensitive products to maintain nutritional and sensory properties while ensuring safety. Shelf-stable products like canned goods require sterilisation and airtight packaging, whereas frozen products rely on low-temperature storage to inhibit microbial growth.

(f) Packaging and Labelling

Appropriate packaging materials are selected based on the product's sensitivity to factors such as oxygen, light or moisture. Biopolymer-based or sustainable packaging is often considered. Labels must meet legal requirements and provide clear information about ingredients, nutrition and storage instructions.

(g) Production Scale-Up

Once all aspects are validated, production is scaled to a commercial level, with continuous monitoring to ensure consistency and adherence to specifications.

(h) Launch and Post-Market Monitoring

The product is introduced to the market, with monitoring for consumer feedback and performance. Recipes or processes may be refined based on consumer preferences or new trends.

Reference

Stoeckel M, Lidolt M, Stressler T et al (2016) Heat stability of indigenous milk plasmin and proteases from Pseudomonas: a challenge in the production of UHT milk products. Int Dairy J 61:250–261. https://doi.org/10.1016/j.idairyj.2016.06.009

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Dairy and Meat Analogues

Lisa M. Berger, Monika Gibis, and Jochen Weiss



Fig. 21.0 Milk and meat analogues (▶ https://doi.org/10.1007/000-hv2)

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The demand for plant-based alternative products is steadily growing due to ethical reasons, sustainability concerns or health aspects. Alternatives can be manufactured from plant-based protein sources to mimic characteristics of animal-derived products, including their optical appearance, flavour, texture, nutritional value, functionality or purpose of use. Common plant-based protein sources employed in the production of these alternatives are legumes, nuts, oilseeds, cereals or pseudocereals (McClements and Grossmann 2022; Plamada et al. 2023). Additionally, an increasing number of novel plant-based protein sources are being investigated for their potential use in alternative meat and dairy products. This chapter highlights key components of the value chain in the production of meat and dairy alternatives. It starts with the characterization and extraction of plant-based proteins and challenges associated with their use in alternative products. Subsequently, the chapter delves into the production processes of meat and dairy alternatives, highlighting technological innovations and processing approaches.

Learning Objectives

After studying this chapter, you will…

- …be able to name characteristics of plant-based proteins (see ► Sect. 21.1).
- …be able to explain the extraction of plant-based proteins (see ► Sect. 21.1).
- …be able to discuss the requirements for production of plant-based alternatives (see ► Sects. 21.1, 21.2, and 21.3).
- …be able to illustrate the production of meat and dairy alternatives (see ► Sects. 21.2 and 21.3).

21.1 Alternative Proteins

21.1.1 Introduction

The term ‘alternative’ has not uniformly been defined but generally refers to proteins whose production is associated with a low CO_2 footprint, indicative of them needing less resources than “conventional” proteins. This includes a lower land, water & energy use and/or a lower environmental impact (e.g. due to decreased methane emissions). The first generation of meat alternatives or analogues often consisted mostly of polysaccharides and fats. However, since polysaccharides are mostly linear molecules with greatly varying molecular weights and are as such much less well defined than proteins, the first wave of meat and dairy analogues did not perform well when it came to consumer acceptance. Their underlying network structure caused them to be rather brittle and weak providing little elasticity, which is essential to have products that mimic the texture of meat or cheese upon consumption. Moreover, with very few exceptions, polysaccharides are not surface-active and therefore cannot stabilize emulsions or foams, which are often essential base structures needed to create dairy or meat analogues. Finally, solubility and water binding capacity of polysaccharides are typically not salt or pH-dependent, and therefore these in food technology common structure-forming tools cannot not be employed to create suitable structures. Therefore, modern meat or dairy analogues are now based on the use of proteins similar to their animal counterparts.

21.1.2 Protein Structure and Function

Proteins are polymers made of 20 different amino acids. Their existence was first postulated by Jöns Jakob Berzelius in 1838, who derived the term from the Greek word πρωτεῖος (proteios) for *fundamental* or *primary*. He postulated that they possessed a common basic structure, which led to a heated argument with Justus von Liebig, the founder of agrochemistry, who vigorously disagreed with this notion. It took, however, until 1902 when Emil Fischer and Franz Hofmeister finally proved that proteins consist of chains of amino acids that are linked together through a unique bond, the so-called “peptide” bond. The peptide bond originates from

an unusual condensation reaction between the C and N-terminal ends of two amino acids. Unusual because the reaction releases water but is not exothermic and has to be carried out and activated by enzymes. That is different from most other condensation reactions. This allows nature a step-by-step, deliberate and systematic manufacture of highly specific amino acid sequences in proteins. Since multiple condensations can be carried out, it is theoretically possible to create proteins of infinite lengths. In practice, though, kinetics will eventually limit the polymerization reaction such that the molecular weight of several million Daltons is not exceeded. For example, Titin, a protein found in the muscles of mammals, has a molecular weight of 3 million Daltons and consists of about 27,000 amino acids. The peptide C-N bond has a planar geometry and can only rotate to a limited extent. It is thus a very stable bond. In principle, cis–trans isomers are possible, but due to steric reasons, about 95% of all peptide bonds in nature have a trans configuration. The C-N bond in peptides has a shorter length compared to the normal C-N bond, indicative of it possessing a double bond character.

Proteins encompass a class of molecules that can possess an enormous variety when it comes to molecular structures. They are built of 20 different amino acids that exist in nature. Consider, for example, the case that a protein may consist of 100 amino acids linked in sequence by 99 peptide bonds, then a theoretical number of 1.27×1030 potential combinations emerges, showing the enormous possible variability of protein biosynthesis. It is important to know that humans, however, can only synthesize 10 of the 20 possible amino acids, meaning that the other 10 have to be taken in through dietary measures, since all are required to build the proteins essential for human metabolism. In contrast, plants can synthesize all 20 amino acids. It should be noted, though, that, not every plant contains all 20 amino acids, and thus combinations are needed to cover the required intake for humans. In contrast, milk and meat are complete sources and they contain all essential amino acids.

The functionality of proteins depends largely on their structure, which is governed by the sequence of amino acids in the chain, and a process called *folding*. Folding is essential for proteins to assume their biological function and is based on subsections in the protein, associating with each other. This association may occur locally at certain places in the molecule, giving rise to so-called sheets or helices or throughout the entire polymer, leading to a highly complex overall three-dimensional arrangement, which determines protein properties. Folding is strongly influenced by environmental conditions such as pH, temperature, pressure and ionic strength, and accordingly, changes in these environmental parameters affect physical, chemical, physiological and techno-functional properties. To build protein-based foods, the latter is of particular importance, and includes, for example, smell, taste or toxicity, but also the nutritional value of proteins. Many of these are a direct result of the structure of the protein, something that has been described in the form of different structure-function relationships.

21.1.3 Sources of Alternative Proteins

Proteins can be derived from all living organisms, but for use in food technology, some classes of proteins are better suited to building products than others. One of the key classification schemes that explains these differences is the Osborne fractionation scheme. Thomas Burr Osborne (1859–1929) was a biochemist who was particularly known for his work on proteins from seeds, exploring their nutritional significance. He proposed that an organism may contain a large variety of different proteins, and that their behaviour and nutritional significance depend especially on their solubility. Subsequently, he was able to derive four different fractions of proteins from seeds, namely albumins (water soluble), globulins (salt soluble), prolamines (alcohol soluble) and glutelines (alkaline soluble). Osborne's discovery provides an understand-

Table 21.1 Albumin, globulin, prolamin and glutelin content (in% of dry matter) of various plant-based proteins

	Albumin	Globulin	Prolamin	Glutelin
Solubility	Water	Salty solution	Ethanol 70%	pH > 11
Function in plant	Physiologic	Storage	Storage	Storage
Soy bean	10%	90%		
Pea	20%	65%		15%
Faba beans	25%	55%		20%
Sunflower	20%	60%	5%	15%
Rapeseed	50%	25%	5%	10%
Mil	8%	4%	46%	42%
Wheat	5%	10%	45%	40%

ing of one of the key differences between animal-derived and various alternative proteins, namely that they differ substantially in the amount of each of these fractions that one can find in the raw material. While milk and meat contain a lot of albumins and globulins, plants also contain significant amounts of glutelins and prolamins. Moreover, between different plants, there are substantial differences in the presence of each of these individual fractions as shown in Table 21.1, which lists albumin, globulin, prolamin and glutelin content for a few plant-based sources of alternative proteins.

This stark difference in the composition of proteins between animal-derived and alternative proteins is based on their role within the originating organism. In plants, proteins often have a simple nitrogen storage function, providing nitrogen to the budding plant, while in animals, they must bind calcium and vitamins (such as in milk) to foster growth of the young animal or provide motility (such as in meat) to mammals. It is therefore not surprising that it may be quite challenging to build a meat analogue from plant proteins since their structure and function may differ profoundly from those found in animals. Today, a range of different raw materials is investigated as sources for alternative proteins and to then build meat or dairy analogues. While the first generation of alternative products still used some animal proteins (such as egg), second, third and fourth generation products are using proteins from plants, insects, microbes or animal cell cultures (Table 21.2).

The first 'alternative' protein preparations that were produced on a large scale to yield plant-based meat or dairy alternatives were derived from seeds (e.g. soy) or legumes (e.g. pea), and production volumes of protein preparations have by now grown to where global markets can be served. Therefore, most analogues currently still consist of plant proteins, and discussions in this chapter on meat and dairy analogues focus on the manufacture of products from such preparations. However, research is underway to also utilize microorganisms such as yeast or microalgae (see ▶ Chap. 10) to obtain valuable proteins, since they may contain as much as 50% proteins on a dry matter basis. One of the limitations to date is mainly that the production capacities are still low, but for example, large-scale fermenter constructions with volumes ranging in the millions of litre are currently underway.

Table 21.2 Overview of first, second, third and fourth generations of alternative protein sources to build vegan or vegetarian foods that mimic the behaviour of dairy or meat-based foods

New protein Sources/types/category	
1st generation Animal based	Conventional meat: Pork, beef, lamb, poultry etc.
2nd generation Plant based	Pulses/ legumes; seeds; cereals; seaweeds. e.g. Pea, soy, chia seed etc.
3rd generation Insect based	Mealworms, crickets, locust/ grasshopper
3rd generation Microbial based	Algae protein; yeast; mycoprotein
4th generation Lab-grown meat	In vitro cultured meat cells

21.1.4 Extraction and Fractionation of Proteins

As mentioned above, in plants but also in microorganisms, proteins serve as nitrogen storage and/or are part of the plant's metabolic machinery. Alternative proteins, therefore, rarely provide structure and are often not per se suitable for use as structural components in alternative (vegan or vegetarian) products. In contrast to animals, where proteins such as collagen, actin and myosin or caseins and lactoglobulins provide, structure such as muscle fibres or milk globules and micelles, the structural components in plants are made out of polysaccharides such as cellulose, hemicellulose or lignin.

Proteins in plants or microorganisms are located inside plant or microbial cells and are not readily accessible. Hence, an extraction is needed. Proteins in plants or microorganisms are also often linked to other components, such as polyphenols, fatty acids, or saponins that may be toxic, antinutritive, or induce off-flavours. In addition, most biomasses contain a lot of different proteins, i.e. there is a wild 'mix' of proteins when it comes to type or molecular weight. As such, not only extraction but also fractionation procedures are needed to obtain well-defined and techno-functional protein preparations that may be used for food design and production.

So-called downstream processes (i.e. processes that follow the primary production of source materials, in contrast to primary production such as the agricultural production of green peas, or the fermentation with yeast) have been developed to 'crack' cellular structures, liberate proteins, and separate them from other compounds. The specific design of these downstream processes depends very much on the nature of the raw material to be used, and bioprocess engineering principles have been developed to address this need. Generally, four steps are carried out to obtain protein concentrates, isolates or meals. In a first step, the tissue is mechanically disrupted using mills or homogenizers that apply high mechanical stresses, thereby disrupting cellular structures. This leads to the enclosed proteins becoming accessible to solvents such as water. In the second step, proteins can then be solubilized, facilitating a subsequent separation from all other compounds. It is important to know that, especially in plant-based raw materials, this step is very important since they often contain all of the four Osborne fractions. Particularly the prolamin and glutelin fractions are not water soluble, and environmental conditions must

therefore be changed to allow insoluble protein complexes to dissociate and go in solution. Temperature, pH, ionic strength, and conductivity are altered by heating or cooling, adding salts, acids or bases, or alcohols to accomplish this. Once in solution, the remaining cellular fragments (e.g. starch kernels, cell walls, fat droplets) can be separated by filtration, sedimentation or centrifugation. The filtrate or supernatant then contains most of the proteins and can be used for the third step to obtain protein concentrates. There, the protein solution is typically again treated with acids or bases and/or the temperature is changed such that proteins fall out of solution, facilitating again a filtration, sedimentation or centrifugation. The proteins are then present in the filter cake or sediment, often at concentrations of 40–50%. A spray drying or vacuum drying process may finally yield powders that have protein contents of well over 80%. Alternatively, membrane separation processes are increasingly used to separate proteins from small molecular weight compounds, eliminating the need to first precipitate the proteins. For medical or personal care applications or if enzymes are needed for catalytic processes, a final gel filtration or ion exchange chromatography may be applied. For food science purposes though, this last step is often omitted since it adds substantially to the costs of the obtained protein preparation. Figure 21.1 illustrates a simple extraction process that is often used in industry to obtain a functional protein preparation from an oilseed.

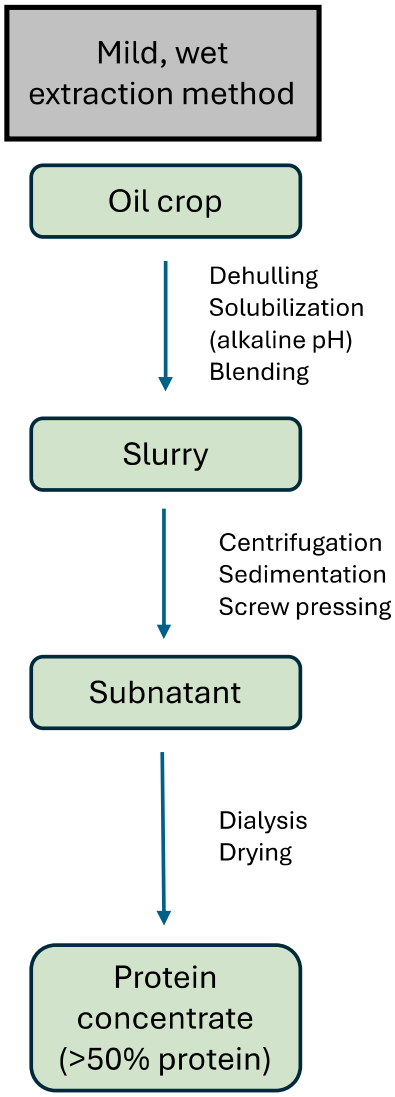


Fig. 21.1 Schematic layout of a mild extraction scheme to produce a plant protein extract

To summarize, the proper design of a protein extraction and fractionation process is a complex matter, since many alternative protein sources contain a large variety of structurally varying proteins. A key goal in the extraction and fractionation is to keep processes as 'mild' as possible in order to obtain proteins that are not denatured and highly functional. The key properties of the raw materials and the cellular structures thereof, such as morphology or mechanical properties, must be known so that disruption, solubilization and precipitation or concentration/isolation can be optimally designed. On a final note, some proteins are also glycosylated, which means they have undergone a so-called post-translational modification in the organisms. This is a process whereby the cell adds further functional groups to the protein backbone, such as phosphor groups or sugars. The role of such post-translational modifications is currently a hot topic in research, and not yet fully understood, but thought to have important influences on the properties of proteins. For example, heavily glycosylated proteins

like those found in microalgae have very different abilities to form gels, emulsions or foams than proteins that are less glycosylated.

21.2 Meat Alternatives

21.2.1 Introduction

Plant-based alternatives to meat and meat products represent the second-largest food industry segment in Germany after milk and dairy product analogues, with sales of approximately 13 million kg per year (Nielsen 2021). Consumer considerations pertaining to religion and health, in addition to the increasing cost of production of animal-based products, contribute to this transition in dietary habits. This change involves a shift away from diets that include animal protein, toward diets that are lower or devoid of animal protein. Plant proteins may prove an effective means of addressing these challenges, as they can be employed in the production of nutritionally valuable products that are attractive to consumers in terms of texture, aroma and taste, and colour and appearance. Alternative proteins are hence increasingly used in the manufacturing of products that could replace meat, and they exhibit a wide range of textures. In particular, solid, sliceable products are experiencing an increase in consumer demand.

Plant-based products that are similar to meat in appearance, texture, taste and colour but are made without meat are often referred to as 'meat or sausage analogues' or 'alternatives'. Guidelines for these alternatives define them as having a high degree of similarity to the meat product in question (Lebensmittelbuchkommission 2024), and to that purpose, sophisticated process and structuring approaches are used to create them to simulate the desired sensory impressions.

21.2.2 Sensory Texture and Anisotropic Matrices

The sensory texture perception of meat is a complex phenomenon, since meat is a hierarchical, ordered and fibre-containing matrix with a high degree of anisotropy (Oppen et al. 2024). The intricate composition of plant-based analogues often makes it challenging to describe or even predict how they are perceived. Nevertheless, muscle-type meat and sausage alternatives must also evoke such sensory impressions. The anisotropy of muscle meat is a key characteristic that explains its high appeal and is likely due to the fact that humans have evolved to associate this structure with a nutrient-rich food source.

The term *anisotropy* is used to describe the directional dependence of material-specific properties. This directional dependence can be due to the composition or structure of the material as well as its production process. The anisotropy can be measured with different methods (optical: light, confocal laser scanning and scanning electron microscopy; mechanical: tensile and Warner Bratzler shear cell; electrical: impedance probe). The anisotropy of foods can be characterized through the calculation of the anisotropic index (AI) (Eq. 21.1), which is defined as the ratio of stress or strain in parallel $\sigma_{\parallel}$ and perpendicular orientations to the fibers $\sigma_{\perp}$, as determined by tensile measurement (Oppen et al. 2024).

$$AI = \frac{\sigma_{||}}{\sigma_{\perp}} \tag{21.1}$$

For this reason, texturized and soluble plant proteins are often used in the production of sausage alternatives.

21.2.3 Ingredients for Manufacturing of Meat Product Alternatives

Meat product alternatives are divided into patty-, burger- or nugget-type, sausage-type, and whole muscle-type products (McClements and Grossmann 2022). For sausage-type alternatives, one has to differentiate between emulsion-type (bologna-type), dry-cured (salami-type) and cooked sausage alternatives (e.g. liver sausage alternatives). The most common sausage analogues are emulsion-type sausage and salami-type alternatives. In meat and sausage products, binding is achieved by solubilizing myofibrillar meat proteins. To do this, the muscle fibre cells are broken down by mechanical force and the myofibrillar proteins, such as actin and myosin, are solubilized by adding salt. These proteins lead to binding and, through heating, to a sol – gel transition in the emulsion-type sausage, making them hard and sliceable. In contrast, in non-heated raw sausage (salami), salt-solubilized myofibrillar proteins are solidified through a drying and fermentation process with a reduction in water content and pH.

For the production of meat-like textures, globular proteins from legumes, cereals, pseudocereals, tubers, oilseeds, fungi and other seeds are particularly suitable (Table 21.3).

Table 21.3 Overview of ingredients used for the manufacture of plant-based alternatives (from McClements and Grossmann 2022)

Ingredients	Source of proteins	Main function
Plant-proteins	Legumes: soy, pea, lupin, fava bean, lentil, chickpea Cereals: wheat, rice, oat, barley, maizePseudo-cereals: amaranth, chia seedsOther edible seeds: buckwheat, quinoaOil seeds: canola, sunflower, hemp, pumpkin, sesame seeds Tubers: potato (Nuts: almond, peanut, walnut, pistachio, cocos more for dairy alternatives) Algae: microalgae, seaweed	Structure, texture, colour, techno-functionality and nutritional physiology
Lipides	Coconut fat and oil, cocoa butter, sunflower oil, rapeseed oil and sesame oil	Taste, texture and mouthfeel
Fat replacers	Oleogels, emulsion-gels and fibres (inulin)	Texture and mouthfeel
Polysaccharides	Native starches, flours, dietary fibres (citrus, bamboo, oat, Psyllium seed husks)	Consistency, oil and water binding
	Binders: Carrageenan, methylcellulose, tara flour, konjac	Thickening and water binding
Flavouring agents	Yeast extract, paprika, sugar, spices and herbs	Flavour and taste (umami)
Colouring agents	Lycopene, beet juice extract, iron oxide, carotene or leghaemoglobin	Imitation of the meat colour
Additives	Tocopherols, zinc gluconate, thiamine hydrochloride (vitamin B1), sodium ascorbate, ascorbic acid, vitamin B12Acidity regulators: Calcium- or sodium lactate, sodium acetate	Improvement in nutritional value and shelf life
Enzymes	Microbial Transglutaminase	Crosslinking and solidification of proteins

Pea protein represents a valuable alternative to soy protein due to its hypoallergenic properties and favourable functional characteristics, which facilitate its use in combination with other proteins such as gluten. Pea protein can be utilized to optimize nutritional and structural properties (Samard et al. 2019). However, the binding characteristics are different from meat proteins. Only wheat gluten is known to be a good binder due to its stickiness and elastic properties. For this reason, binding agents such as polysaccharides are often required.

Binding agents

Binders are an essential ingredient to form meat product analogues, bringing together individual structural elements such as protein fibres and fat particles and also enhancing the consistency of products such as sausage analogues. To achieve this, binders have a high affinity for water or fat and oil, and through their association with these compounds improve gelling, thickening and emulsion stability. This facilitates the production of a heat-stable product with textural properties comparable to those of animal-based emulsion-type sausages. Compounds used include hydrocolloids, such as methylcellulose (~1.5%), starch (~2%), carrageenan, xanthan, konjac or tara gum, as well as fibres (~3–4%). Fibres such as those from citrus peel made from juiced, de-oiled and dried citrus fruits, pea from the pea pod, oat mainly from oat husks, bamboo (mostly made from pre-treated bamboo cane) may also be used for moisture binding and solidification. These fibres also increase the dietary fibre content, which is beneficial from a nutritional point of view.

Micronutrients

Some minerals and vitamins are low or missing in vegan and/or vegetarian diets. Vitamin B12 (Cobalamine) is found only in foods of animal origin in amounts that are sufficient to ensure an adequate supply of the vitamin. Individuals who adhere to an exclusively plant-based diet (vegan) or consume only minimal quantities of animal products are required to take a vitamin B12 supplement (McClements 2023). The estimated value for an adequate intake for adults is 4.0 µg per day. In addition to vitamin B12 and iodine, a vegan diet is requires adequate amounts of essential amino acids, long-chain n-3 fatty acids, vitamin D, riboflavin, calcium, iron, zinc, selenium and vitamin A. These elements are regarded as potentially critical as they are often low in many analogue products (Klug et al. 2024).

Colouring agents

Colorants are required to imitate meat colour or the curing colour of sausages (i.e. colours created by the reaction with nitric oxide and myoglobin to nitrosyl myoglobin, forming stable colour pigment nitrosyl haem after protein denaturation). Caramel colour (E150a-d) (brown) (produced by caramelization of glucose syrup with sulphuric acid in the presence of ammonia), curcumin (yellow) (E100), betanin (E162, water soluble, acid resistant, sensitive to light and high heat) or beet juice extract, carotenoids (yellow-red) (E160, E 161, E 164) such as carotene (E 160a), canthaxanthin (E 161g) and lycopene (E160d, oil-soluble), carotenoid-rich extracts such as paprika oleoresins (E160c), annatto seed extracts (E160b), carrot extract or lycopene-rich extracts from tomatoes can be used for this purpose. The mineral iron oxide red (E 172, Fe_2O_3) can also be used as a heat-stable colouring agent. It is often used in combination with carotene and betanin to produce meat alternative. Naturally occurring anthocyanins (E163) are not heat-stable and change colour with pH. Radish anthocyanin is nevertheless often used in vegan meat alternatives, mainly because it can produce a pink/red hue over a relatively wide pH range (3–6) compared to other anthocyanin sources. The colourant carmine (E120) is a red, heat-stable and pink colourant that is obtained from the cochineal insect (*Dactylopius coccus*) and is often used in sausage products, but cannot be used for vegan and vegetarian foods.

Proteins

In addition to the hydrocolloids previously discussed, a wide variety of proteins are utilized, whether in the form of low- and high-

protein flours (~10–50% protein), concentrates (~50–70%), or isolates (from 80% to ≥90%) (Loveday, 2020). They exert a significant influence on the binding of water and oil, the stability of dispersions, and the solidification of the matrix. Besides the named plant proteins, sunflower, canola, hemp, chickpea, oat, wheat, linseed, lupine, fava bean proteins and others have been used for the production of meat alternatives. Gluten in particular is often used as a binder, resulting in a notable improvement of the texture. The majority of plant proteins exhibit a higher denaturation and gelling temperature than their meat protein counterpart, typically ranging from 70 to 90 °C. For example, pea proteins gel and denature between 75 and 79 °C, which is substantially higher than those required for meat proteins.

A variety of extrusion processes can be used to obtain texturized vegetable proteins (TVP). Both low-moisture (LME) and high-moisture extrusion (HME) (Fig. 21.2) as well as high-shear cells (Fig. 21.3) have been used, resulting in fibrous material with moisture contents above 50 wt.%,). In low-moisture extrusion, protein flours or concentrates are mechanically processed to produce textured vegetable proteins (TVP). These are dry, slightly expanded products that are later subjected to moistening prior to being used in alternative products.

Proteins in the extrudates are mostly in a denatured state. Technofunctional properties decline due to the mechanical and thermal effects of the extrusion process. As a consequence, one can no longer solubilize the proteins in the extrudates, which is why binding

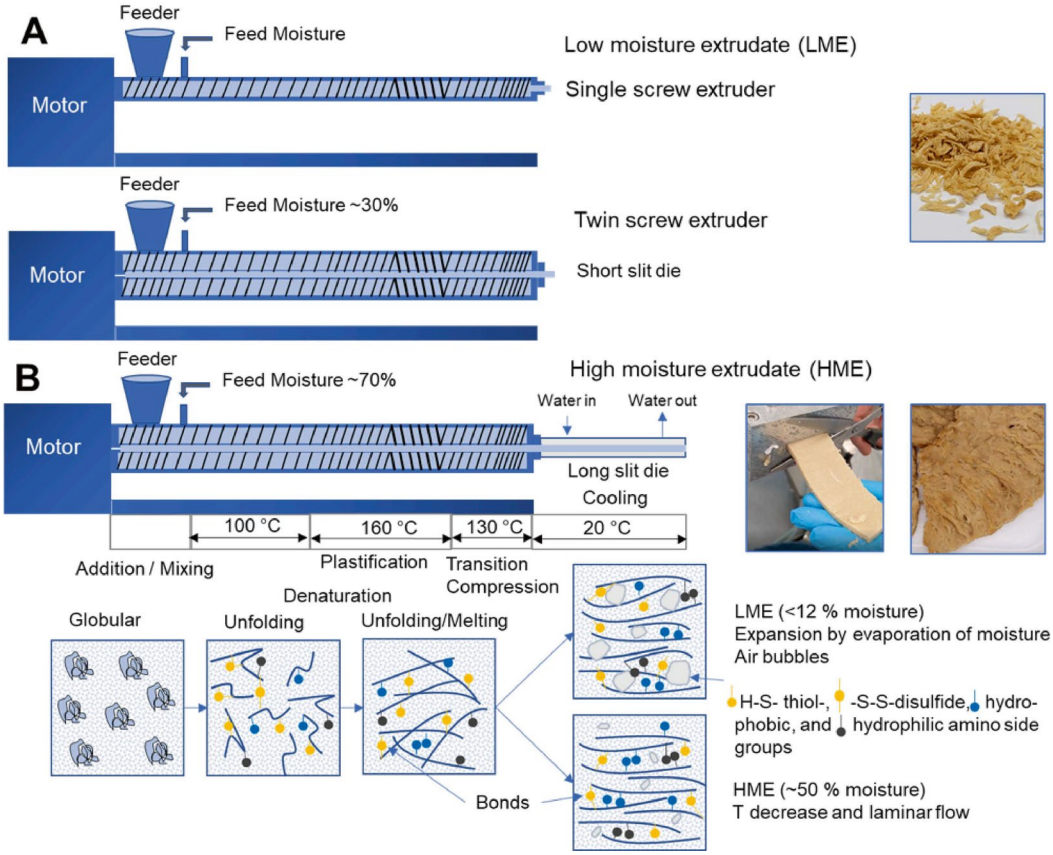


Fig. 21.2 Schematic diagram of low- (**a**) and high-moisture (**b**) extrusion cooking with details of the screw configuration. (Adapted from Smard et al. (2019), Grossmann and Weiss (2021))

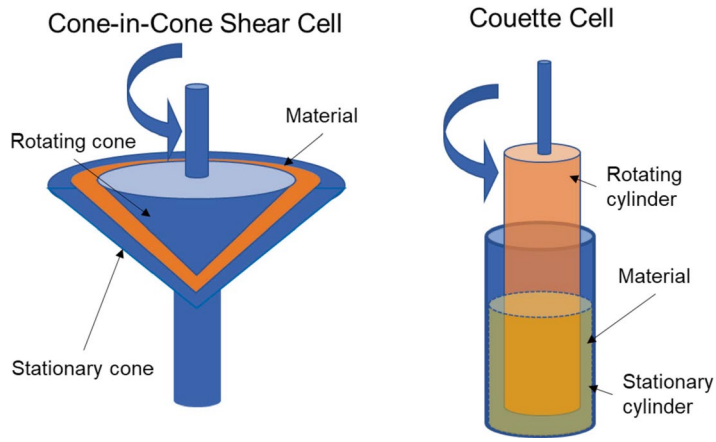


Fig. 21.3 High shear techniques (cone-in-cone- and Couette shear cell) for the production of fibrous protein structures for plant-based meat alternatives. (Adapted from Krintiras et al. (2015), van der Goot et al. (2008))

agents have to be added. There, protein fibres are incorporated in the outer phase as inert filler particles, resulting in the texture of the binder matrix (e.g. gluten network, hydrocolloid gel, protein gel) playing a substantial role in the final texture of the product. Suitable binders must have a certain degree of stickiness with both cohesive and adhesive properties, as well as the ability to solidify (Herz et al. 2023).

21.2.4 Texturization Process of Proteins

Rotational Shearing

Two systems have been described, namely the cone-in-cone system and the Couette shear cell (Fig. 21.3). A Couette cell is defined as a concentric cylinder device comprised of an inner rotating cylinder and an outer, stationary cylinder. Both the inner cylinder and the stationary outer cylinder are subjected to heat. The sample material is positioned within the shearing zone, that is the space between the two aforementioned cylinders. Process parameters that can be changed are temperature, gap size between cylinders, rotation speed and process time. In the cone-in-cone process, protein dispersions are similarly positioned within the space between an inner rotating and outer stationary cone. Through shear and heat, proteins are plasticized and then solidified by cooling.

Extrusion

Extrusion is a shaping process that was originally employed primarily for thermoplastics. The adaptation of this process to food technology is a relatively recent development. In this process, semi-solid to viscous masses are continuously extruded from a shaping tool (nozzle, mouthpiece or die) under high pressure and at elevated temperatures. This results in the formation of a body of varying length, with a cross-section that is typically similar in dimensions to the used shaping tool. The generated product is referred to as an 'extrudate'. Both single-screw and twin-screw extruders are used in the food industry (Sui et al. 2024; Wittek et al. 2021). In the latter, the flow is achieved by volume changes between the co-rotating and intercalated screws, while in the former, the flow is achieved by friction between the material and the screw surface. The geometry of the nozzle is of particular importance in the shaping of the material, and various die geometries exist to generate flakes, strands, or even co-extruded loops using different materials.

The physical processes occurring within the die are intricate and multifaceted. These include turbulent or laminar flows, varying frictional forces and pressures, velocity gradients in the direction of flow or in the transverse direction, as well as variations in residence time in certain sections, including the die. Thermodynamic characteristics (e.g.

density, heat capacity, and thermal conductivity) change as a result of the passage through the device, causing molecular interactions such as Van der Waals interactions, hydrophobic interactions, and hydrogen and disulfide bond formation, to occur. These interactions persist even after the materials exit the extruder. High temperatures during extrusion cooking inactivate antinutritional factors (e.g. antitrypsin factor, lectins) and improve digestibility but may decrease protein digestibility and lysine bioavailability.

In the case of low-moisture extrusion, approximately 20–40% water is added to the feedstock and often single-screw extruders are employed. The extrudates have residual moisture contents of less than 12%, thereby rendering them shelf-stable but requiring hydration prior to use. In high moisture extrusion, water contents exceed 40% and twin screw extruders, facilitating superimposition of high temperatures of >100 °C are used. A cooling die prevents expansion of the matrix, facilitating the formation of protein fibres. Velocity and temperature gradients play a crucial role in product structuring, with multiphase morphologies emerging consistent with a typical Hagen-Poiseuille flow profile (Wittek et al. 2021).

21.2.5 Muscle-Type Alternatives

Meat alternatives or imitation meat are foods that resemble meat in terms of taste, feel or protein content, but are made from non-animal materials. Firm, aromatic mushrooms (e.g., oyster mushrooms), protein-rich plant products (e.g. tofu, tempeh, and seitan), and imitation products made from textured soy, peas, wheat protein (gluten), Quorn®, and/or egg white are described in the following sections.

▪ Tofu

The production of tofu encompasses first a selection of raw soybean seeds. Soybeans are then subjected to an overnight soaking, followed by grinding, heating, and filtration to obtain a liquid soy milk. A coagulant (calcium sulphate or *nigari*) is added at moderate temperatures, and the rapidly aggregating soy product is then transferred into rectangular sieve molds and compressed until a specified consistency is attained. The final product may then undergo smoking, maturation, and drying. The choice of coagulant, such as calcium chloride, calcium acetate, calcium lactate, magnesium sulphate or tri magnesium citrate, and the extent of processing, including pressing and centrifuging, can significantly impact the quality of the finished tofu (Zheng et al. 2020). Additionally, the use of mixed coagulants, such as calcium sulphate-magnesium chloride salt mixtures (Wang et al. 2019), or microbial transglutaminase in conjunction with glucono-δ-lactone (GDL), may be utilized to achieve diverse textural characteristics in tofu. It should be noted, though that tofu is an isotropic product lacking fibrous characteristics.

▪ Tempeh

The tempeh production has its traditional origins in Java (Indonesia). In contrast to tofu, tempeh is not produced from soy milk but rather derived from whole soybeans. The beans are washed and soaked for 24 h in cold water. After boiling for 5–10 min, beans are soaked in cold water for another 24 h. The shells are then removed and the beans sterilized for 30 min. Molds belonging to the Rhizopus species (e.g. *Rh. oligosporus, Rh. stolonifer, Rh. oryzae,* or *Rh. arrhizus*) are then added to initiate the fermentation. The fungal mycelium grows around the soybeans and binds them cohesively together. Mild acidulants, such as vinegar, lactic acid or acetic acid are added to maintain a pH of 3–5, limiting the proliferation of spoilage microorganisms. The taste of tempeh is often described as mushroom-like, meaty, and nutty, and similar to tofu, tempeh lacks any fibrous structure.

▪ Seitan

Seitan has been produced as a meat alternative in China since the sixth century (known as *Miànjīn* in Chinese), and is a staple food in parts of Japan, Korea and Southeast Asia. To produce seitan, wheat flour is repeatedly kneaded and washed with water to gradually remove the starch granules from the wheat

flour, leaving behind a gluten-rich protein matrix. Additives such as colours, flavours, acidifiers, etc., may be added, and the masses are then solidified by cooking or steaming. A meat-like flavour and consistency are achieved through marination with e.g. soy sauce, seaweed, and spices. Seitan can be used for frying, deep-frying and oven baking. An additional option is to dry and grind the separated gluten into a powdered form to be rehydrated for later use. Seitan has a meat-like, fibrous consistency and is often used as an alternative for Schnitzel, goulash or minced meat products.

▪ Quorn®

Quorn is a product developed in the UK from the fermented mycelium of the tubular fungus *Fusarium venenatum*. Quorn typically comprises 10–15% mycoprotein, which contains all essential amino acids. Its protein content is comparable to that of pulses. Quorn may be enriched with vitamins and minerals and processed with egg white from chicken eggs as a binding agent in a patented process. In contrast to meat, it provides minimal iron but contains dietary fibres. The fat content varies between 3 and 19 g/100 g, depending on the product.

▪ Textured vegetable protein

TVP has been used as a meat replacer, and its production entails first a grinding of soybeans, followed by a pressing to remove soybean oil. Alternatively, rehydrated powders of defatted soy protein isolates or concentrates may be used. The sough-like masses are extruded under high pressure in a twin-screw extruder, resulting in a fibrous and partially porous texture as described above. Subsequently, texturates may be ground and dried for later use. Dried soy extrudates are hydrated with hot water prior to further utilization, resulting in a volume increase of approximately 2.5 to a maximum of 3-fold. The process is increasingly also used for other legume proteins.

21.2.6 Burger-Type Alternatives

These products are largely made from the aforementioned muscle-type alternatives. The manufacturing process is shown in

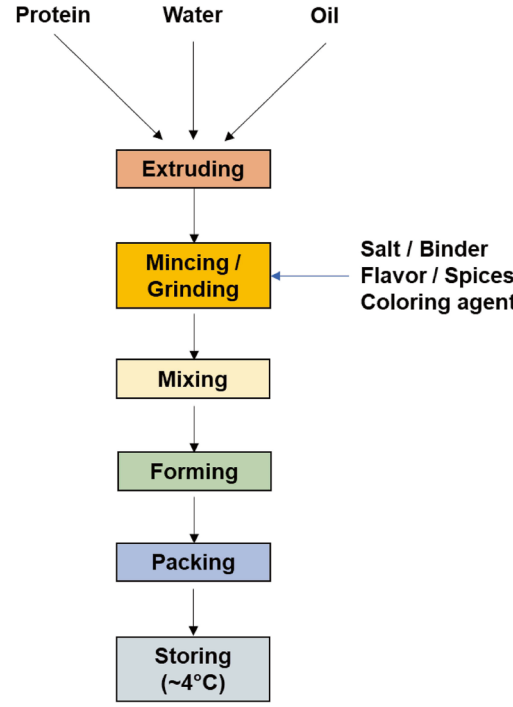


Fig. 21.4 Flow chart of manufacturing process of patty alternatives

Fig. 21.4. Typical formulations contain a large variety of ingredients ranging from binders, protein extrudates, and structured fats or oils, spices, salts and colours. To enhance shelf life, antioxidants and antimicrobials may be added. Recently, the addition of protective microbial cultures has also been reported.

21.2.7 Sausage Alternatives

▪ Emulsion-type sausage alternatives

Figure 21.5 illustrates the production process of an original emulsion-type sausage in comparison to a sausage alternative product. Emulsified sausages are defined as those that have undergone a heating process, whether by scalding, baking, frying, or other means, prior to their final preparation. Such products are typically labelled as sausages, with the addition of specific names such as 'Wiener,' 'Frankfurter,' 'Lyoner,' or 'Mortadella'. The following ingredients are in accordance with the established guidelines for meat and meat

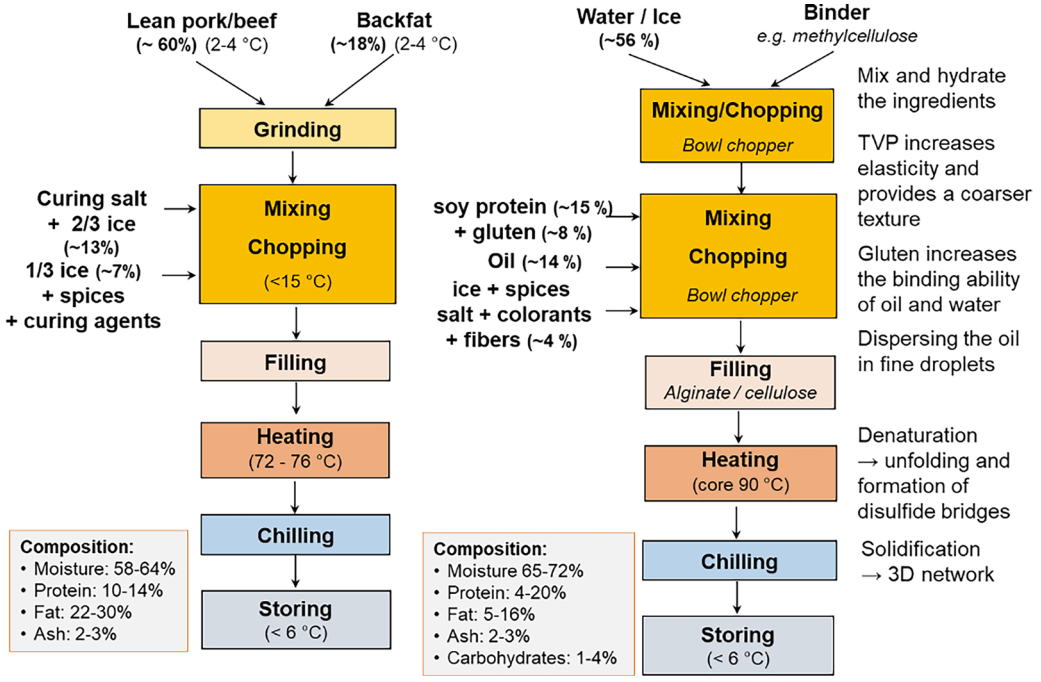


Fig. 21.5 Flow charts of manufacturing processes of emulsion-type sausages and alternatives. (Adapted from Gibis and Weiss (2024))

products: raw minced beef, pork, and/or poultry meat; fat; ice; salt (sodium chloride), which may also be in the form of curing salt containing 0.5% sodium nitrite and 99.5% sodium chloride, other chopping aids (e.g. sodium diphosphate or polyphosphates), and spices. They are characterized by a firm consistency (both in the cold and warm stage) due to the muscle protein being more or less cohesively bound and cross-linked during the heat treatment. Ingredients for alternatives to sausages contain texturized vegetable proteins (TVP) as well as protein powders from pulses such as soy or pea, potato and/or wheat protein (gluten), water, fats, and binding agents such as methylcellulose (~1.5%), carrageenan, xanthan, konjac or tara gum, fibres (~3-4%), starch (~2%), as well as salt, colorants and spices.

Dry-fermented sausage alternatives

Dry-fermented sausages such as salami are widely consumed globally due to their palatable flavour, texture and visual appeal. The primary components utilized in the production of salami are minced fat and meat. The fat is reduced to particles of varying diameters (approximately 3–15 mm) through a process of mincing, which involves the use of a grinder. Subsequently, the product is subjected to fermentation using starter cultures such as lactic acid bacteria or an acidifier, such as glucono-δ-lactone, and then dried, which ultimately results in the formation of its distinctive quality attributes and an extended shelf life. The final product possesses a firm texture that contributes to its functionality and mouthfeel. To achieve a product with comparable behaviour and appearance, different strategies have been developed to mimic the fatty and lean regions using plant-derived ingredients. The flow-chart of both dry fermented sausages and plant-based alternative (salami) processes is shown in Fig. 21.6. Most commonly, hydrogels produced from soluble vegetable proteins and mixtures with polysaccharides (carrageenan, tara gums) and TVP, produced by extrusion, or wheat gluten, are employed as a replacement for the lean meat content. As a plant-based substitute for

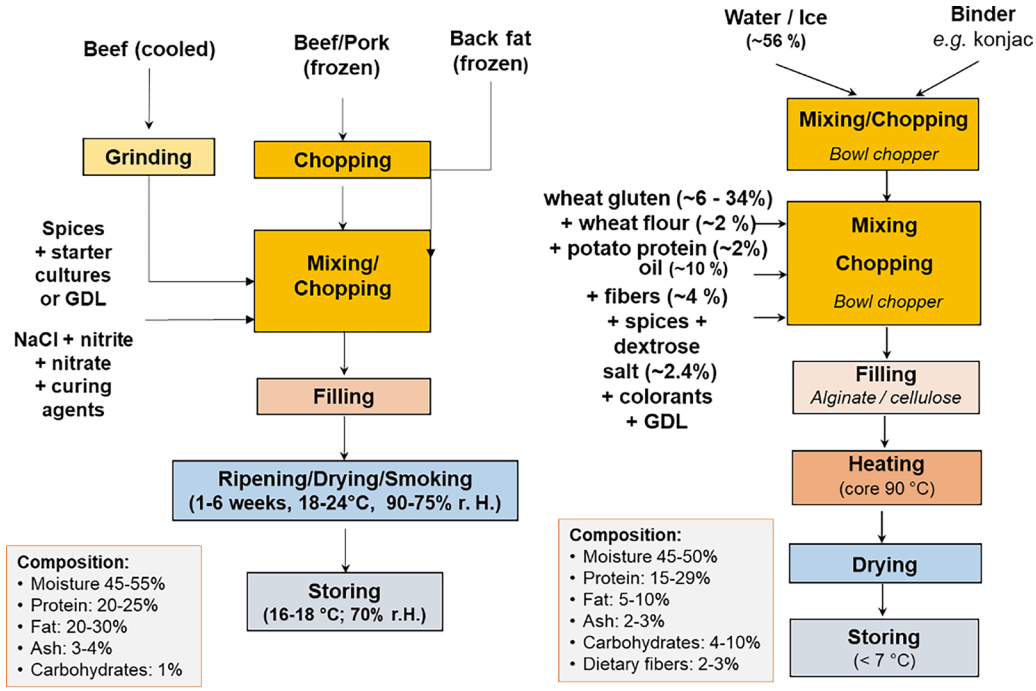


Fig. 21.6 Flow charts of manufacturing processes of dry-fermented sausages and alternatives. (Adapted from Gibis and Weiss (2024))

the fatty regions in salami, fats such as hydrogenated coconut fat with melting points of 36–40 °C are used. An alternative is to use so-called 'structured fats and oils', which involves the creation of a highly concentrated, protein stabilized emulsion gel or an oleogel that mimics the plastic properties of a high-melting fat.

21.3 Dairy Alternatives

21.3.1 Introduction

Dairy alternatives are plant-based products designed to replicate the characteristics of traditional dairy products. This chapter will focus on dairy alternatives in various forms, including liquid, gel-like and (semi-)solid products with similarities to traditional dairy products. An overview on the dairy alternatives and their structural formation is illustrated in shown in Fig. 21.7.

21.3.2 Liquid Products (Plant-Based Milk Drinks)

Milk from cows contains about 3.2% protein, 3.9% fat, 4.6% carbohydrates and 0.7% ash, in which the components are present as dispersed particles (fat globules, casein micelles) or dissolved (whey proteins) (Belitz et al., 2007). Cow's milk is characterized by its low viscosity (2–3 mPas) and whitish turbid appearance, caused by the scattering of the light at the oil-water interface of fat globules and casein micelles (McClements and Grossmann 2022). To design plant-based milk drinks with comparable physicochemical characteristics, such as appearance, flavour or mouthfeel, colloidal attributes must be simulated. Additionally, key components such as proteins, fat and sugars must be substituted by plant-based sources. This can be achieved through either the disruption of plant materials (referred to as the 'tissue disruption method') or via emulsification of individual ingredients (referred to as the

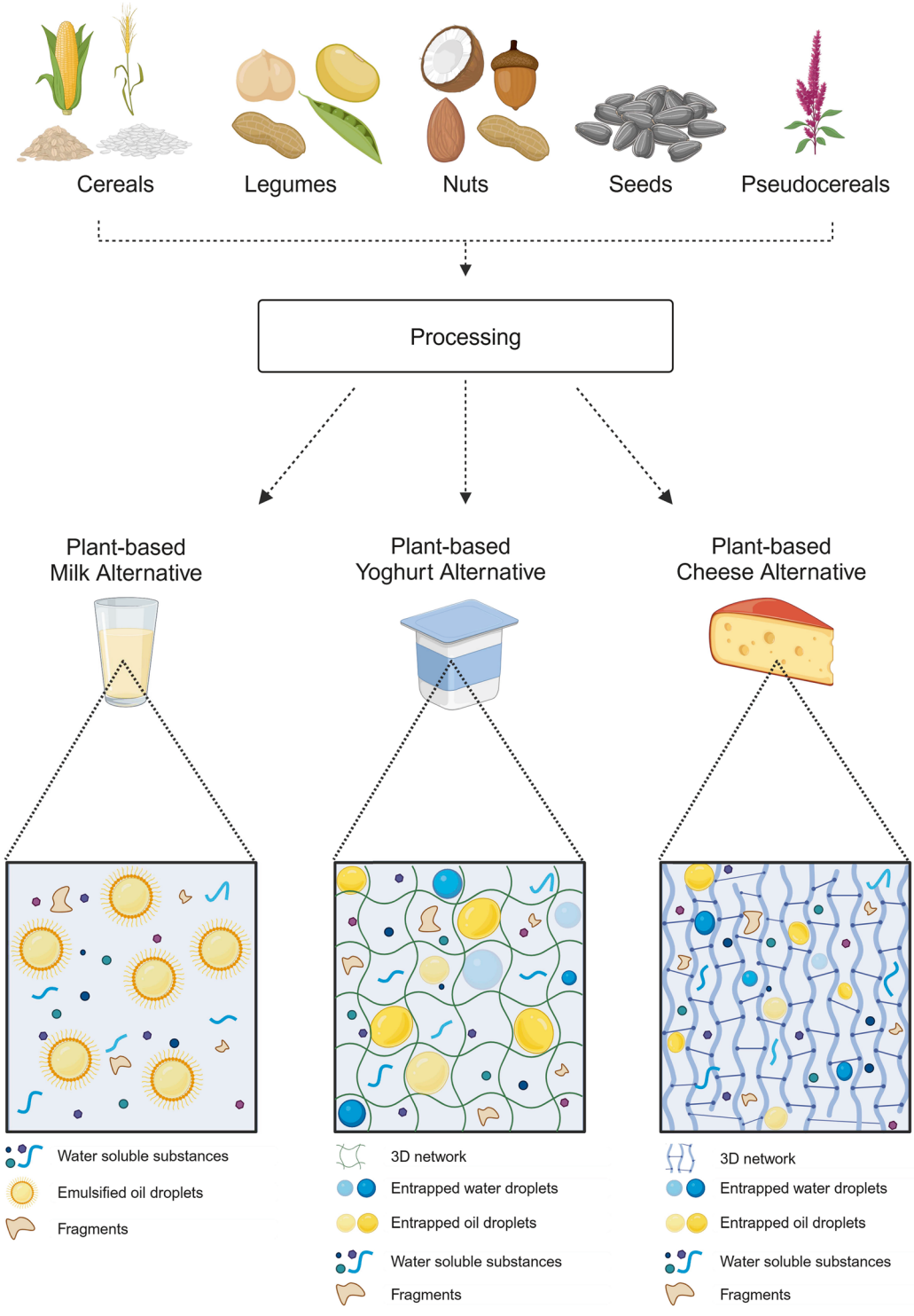


Fig. 21.7 General overview of the production of plant-based dairy alternatives and structure formation (Created in ► BioRender.com)

'emulsification method') (McClements and Grossmann 2022; Plamada et al. 2023).

Tissue disruption method

This method is often used for raw materials containing a significant amount of fat, e.g. soybeans, cashews, coconut, or oats. Mechanical forces are applied to first fragment the raw material. Additionally biochemical agents (i.e. enzymes) can further break down the material via hydrolysis (McClements and Grossmann 2022). Figure 21.8 shows a general production flowchart of a plant-based milk alternative using the tissue disruption method. The specific processing steps vary depending on the raw material used. In the first step, the raw material is prepared by either dry or wet milling, leading to a plant tissue dispersion. Optionally, the disrupted biomass may be roasted and/or soaked to improve flavour and appearance. Since the dispersion contains plant material fragments of different sizes, shapes and chemical compositions, insoluble particles are mechanically

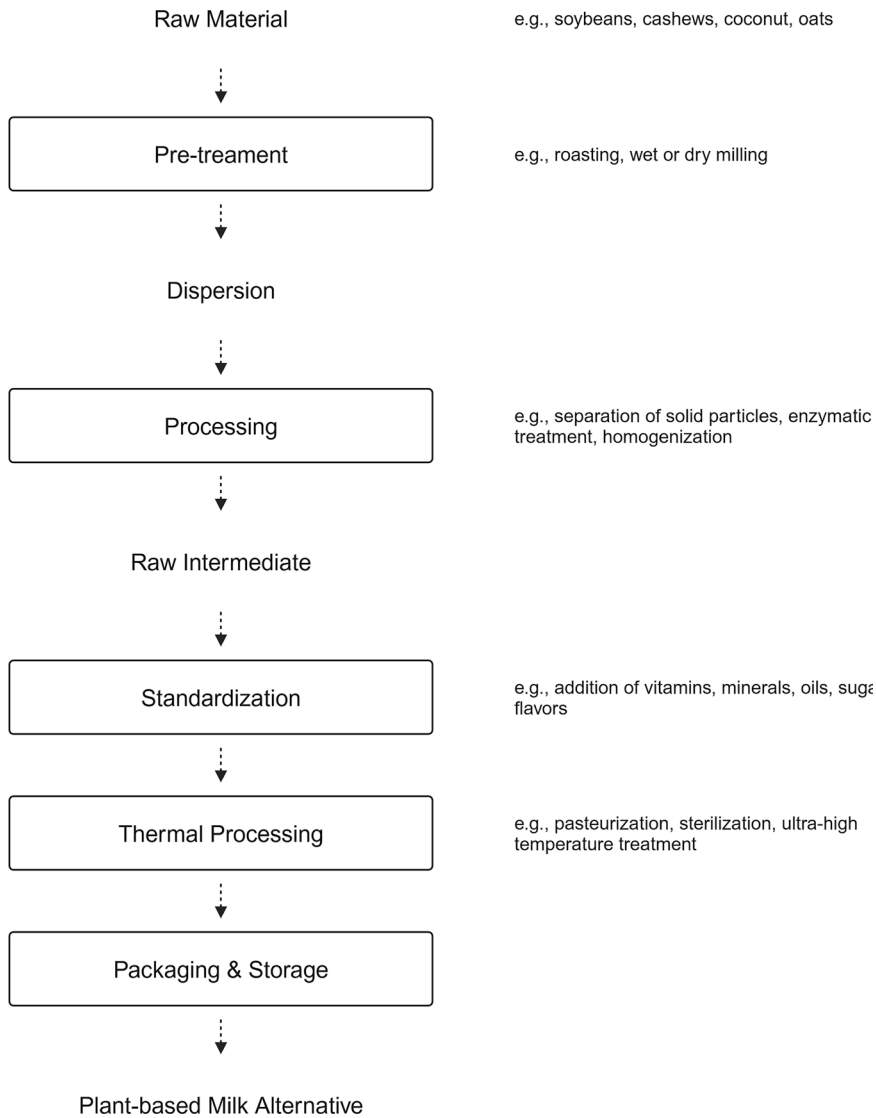


Fig. 21.8 General production flowchart of a plant-based milk alternative using the "tissue disruption method". ((Adapted from McClements and Grossmann 2022) Created in ► BioRender.com)

removed from the dispersion to ensure a homogeneous, stable product with a pleasant mouthfeel. This can be done by filtration, sedimentation or centrifugation. Adding enzymes to hydrolyse starch, fibres, or cell walls can further improve the sedimentation stability of plant-based milk alternatives. During homogenization of the intermediate product, mechanical forces are applied to reduce the particle size, which prevents creaming or sedimentation. This is governed by Stokes Law, which states that the velocity of sedimentation is proportional to a variety of factors such as the particle size, density, and viscosity. Additional ingredients, such as vitamins, minerals, oils, sugars, or flavours can then added to improve product acceptance and nutritional value (McClements and Grossmann, 2022; Plamada et al. 2023). Before filling and packaging, most plant-based milk alternatives must undergo a thermal treatment to ensure food safety and prolong shelf life. Thermal treatments carried out include pasteurization (ca. 72–75 °C for 15–30 s), sterilization (ca. 110–120 °C for 10–30 min) or ultra-high temperature treatments (ca. 135 °C for a few seconds). Thereby, products attain shelf lives that range from 10 days at <6 °C to several months at room temperature.

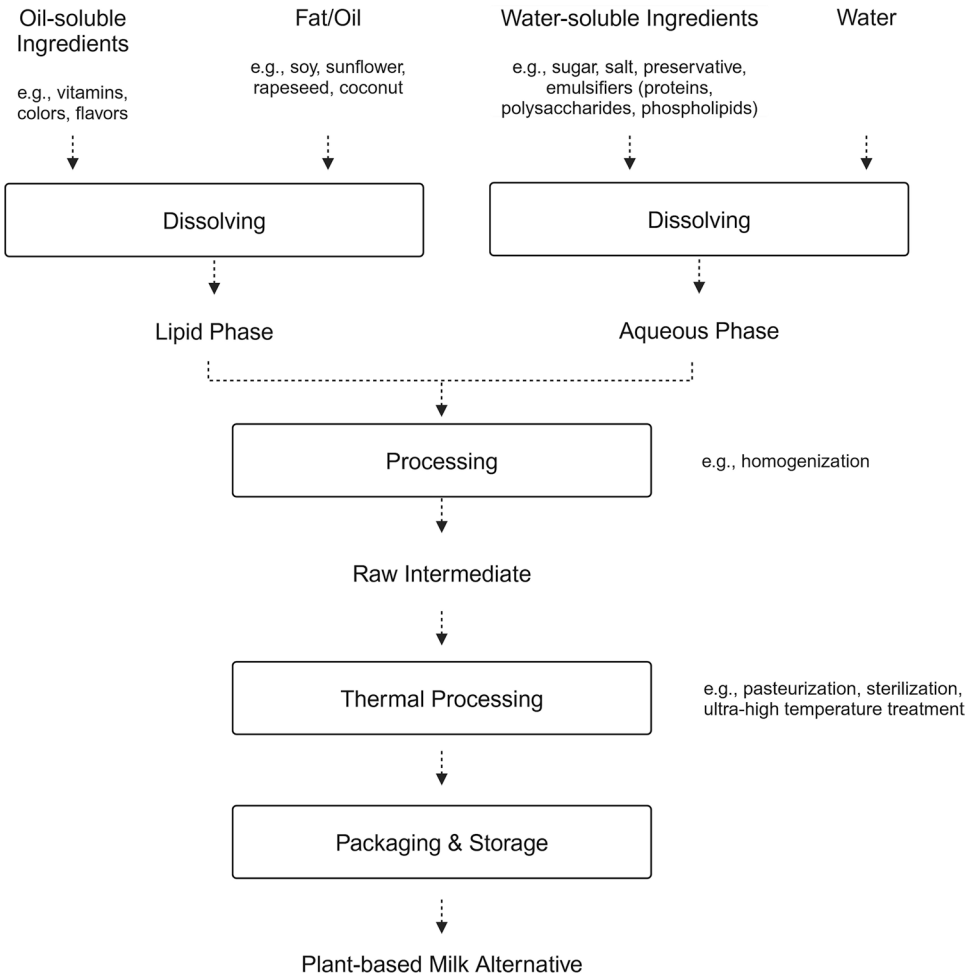


Fig. 21.9 General production flowchart of a plant-based milk alternative using the "emulsification method". (Adapted from McClements and Grossmann 2022) (Created in ► BioRender.com)

Emulsification method

This method is depicted in Fig. 21.9 and involves the use of previously extracted and refined raw materials, mainly plant-based oils and fats, emulsifiers, water, plant-based protein concentrates or isolates, and other additives (McClements and Grossmann 2022). Oil-soluble components, such as vitamins, colours or flavours, are pre-dissolved in the oil phase. Typical plant-based sources for oils and fats are corn, sunflower, canola, palm, coconut or olive. Water-soluble components, such as sugars, salts, preservatives or texturizers are dissolved in the water phase together with water-soluble emulsifiers such as plant proteins, polysaccharides, or polysaccharides. The ingredients are then mixed using high shear dispersion methods such as colloid mills or high-pressure homogenizers in order to create oil-in-water emulsions. Similar thermal processing approaches as listed above in the tissue disruption method are then customarily applied to ensure product stability and safety. Finally, while vitamins and minerals are often added to plant-based milk alternatives to improve their nutritional values, this is still an area requiring improvement. For example, dairy proteins afford a full amino acid profile, and casein micelles carry an extraordinary amount of calcium and Vitamin D due to their biological structure. In contrast, added minerals and vitamins have lower stability and bioavailability. Some improvement comes from combining different plant-based protein sources to modulate nutritional profiles, providing a better amino acid composition (Plamada et al. 2023).

21.3.3 Gel-Like Products (Plant-Based Yoghurt)

Yoghurt is a fermented gel-like product made from cow milk. During fermentation of milk, lactic acid is produced, lowering the pH and enabling the aggregation of casein micelles. This leads to the formation of a 3D protein network and a sol–gel transition, increasing the product's viscosity. The protein network entraps other components, such as fat or water, resulting in the characteristic texture of yoghurt (Belitz et al. 2007). Figure 21.10 shows the production flowchart of a plant-based yoghurt alternative. The basis to produce plant-based yoghurt alternatives is to have a plant-based milk alternative available, which can be made from, e.g. soy, oat, pea, hemp, almond, cashew, coconut or lupin. The plant-based milk alternative is standardized and other ingredients, such as hydrocolloids, sugars, stabilizers, aroma compounds, salts, minerals or vitamins, are added prior to fermentation. Due to the differing functionalities of plant and dairy proteins, thickeners, structure enhancers or other additives may be necessary to form a gel-like yoghurt structure. The fermentation is performed by adding starter cultures to the plant-based milk and incubating the system at conditions conducive to bacterial proliferation and production of metabolites (ca. 40–45 °C, several hours) (McClements and Grossmann 2022; Montemurro et al. 2021). Depending on the desired product properties, down-stream processing can include, e.g. stirring, heating or adding flavour components, fruits, vitamins, or minerals. Finally, the yoghurt is aseptically filled and stored refrigerated. Fermentation can also take place directly in the serving-size packages. In this case, the filling step is performed before the fermentation. Fermentation is not only important for structure formation but also reduces antinutritional compounds, e.g. condensed tannins, saponins, phytic acid, α-galactosides, trypsin and protease inhibitors, and increases nutritional, sensory, and technological properties of plant-based proteins (McClements and Grossmann 2022; Montemurro et al. 2021; Plamada et al. 2023). To further modulate the texture, appearance, taste and smell, as well as nutritional values of yoghurt, a careful selection of plant protein sources is carried out, often leading to mixtures of proteins being used.

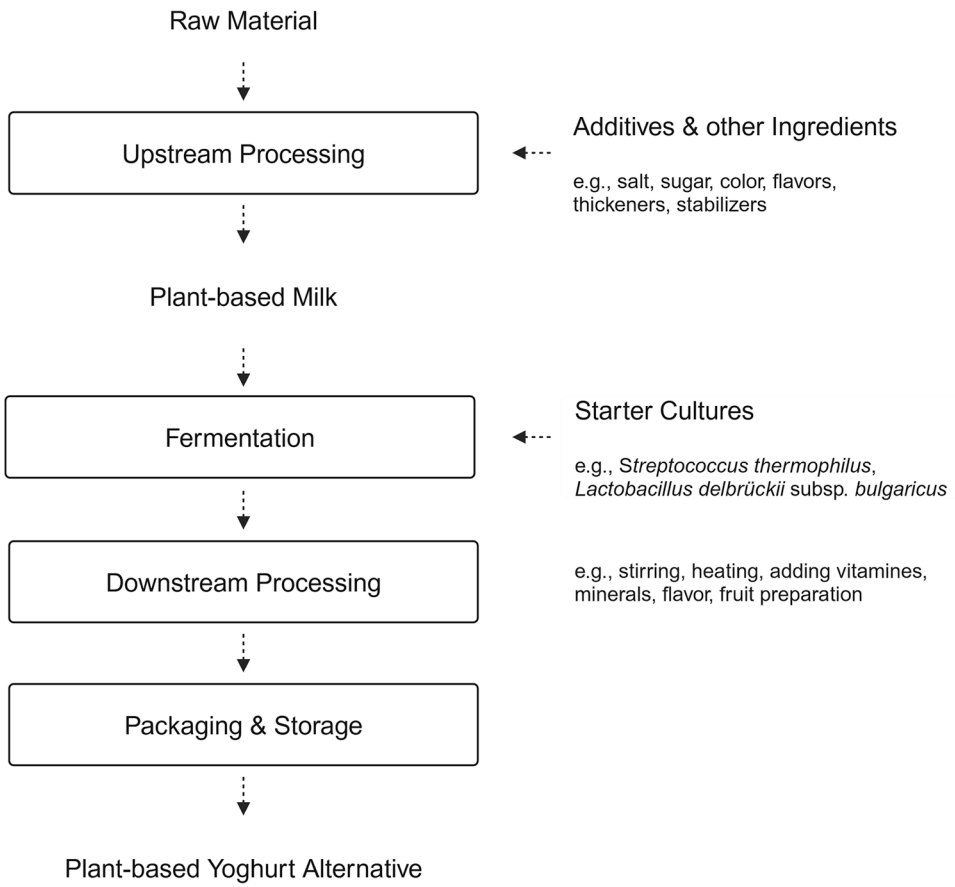


Fig. 21.10 General production flowchart of a plant-based yoghurt alternative. (Created in ► https://BioRender.com)

21.3.4 Semi-Solid Products (Plant-Based Cheese)

Cheese is defined as a solid dairy product which is formed by coagulation of the milk protein casein. It can be classified into ripened and unripened varieties as well as categorized according to fat or moisture content (Käseverordnung (KäseV) 1986). The manufacturing process varies depending on the cheese type produced. This chapter focuses on sliceable cheese alternatives. Sliceability and shreddability of cheese is an important property in the food industry and require a sol – gel transition followed by a dewatering, leading to a product with a high dry matter content. The formation of a 3D protein network is induced by acidification (lactic acid fermentation) and/or enzymatic treatments (renneting) (Belitz et al. 2007). In principle, similar to the manufacture of plant-based milk drinks, the production of plant-based cheese alternatives can be done either by a 'tissue disruption' or 'emulsification' method.

▪ Emulsification Method

One distinguishes here between either a carbohydrate- or protein-based emulsification. In the carbohydrate-based emulsification approach, the product's texture is formed by thermally inducing a hydrocolloid-based 3D network, while in the protein-based method, the texture is formed by a plant-protein network. Various methods, depending on the gelling agent (protein or hydrocolloid), may be used to induce cross-linking, e.g. thermal treatments, salting-out, pH shifts or enzymatic reactions. Hydrocolloids, such as starches, gellan, xanthan,

agar-agar, and plant proteins (fractions), such as soy, pea, or zein, exhibit thickening, gelling and water-holding properties and are thereby able to form sliceable gels. To modify the textural and functional properties of plant-based cheese alternatives, different sources of hydrocolloids or plant proteins might be combined, as they exhibit specific functionalities and nutritional profiles (Kamath et al. 2022; McClements and Grossmann 2022). Care must be taken though not to combine proteins and hydrocolloids that are phase incompatible. Some proteins and carbohydrates are thermodynamically incompatible leading to them phase separating over time, which would make the formation of a cheese alternative impossible. To produce a plant-based cheese alternative according to the carbohydrate-based emulsification method (Fig. 21.11), the hydrocolloids are emulsified and homogenized

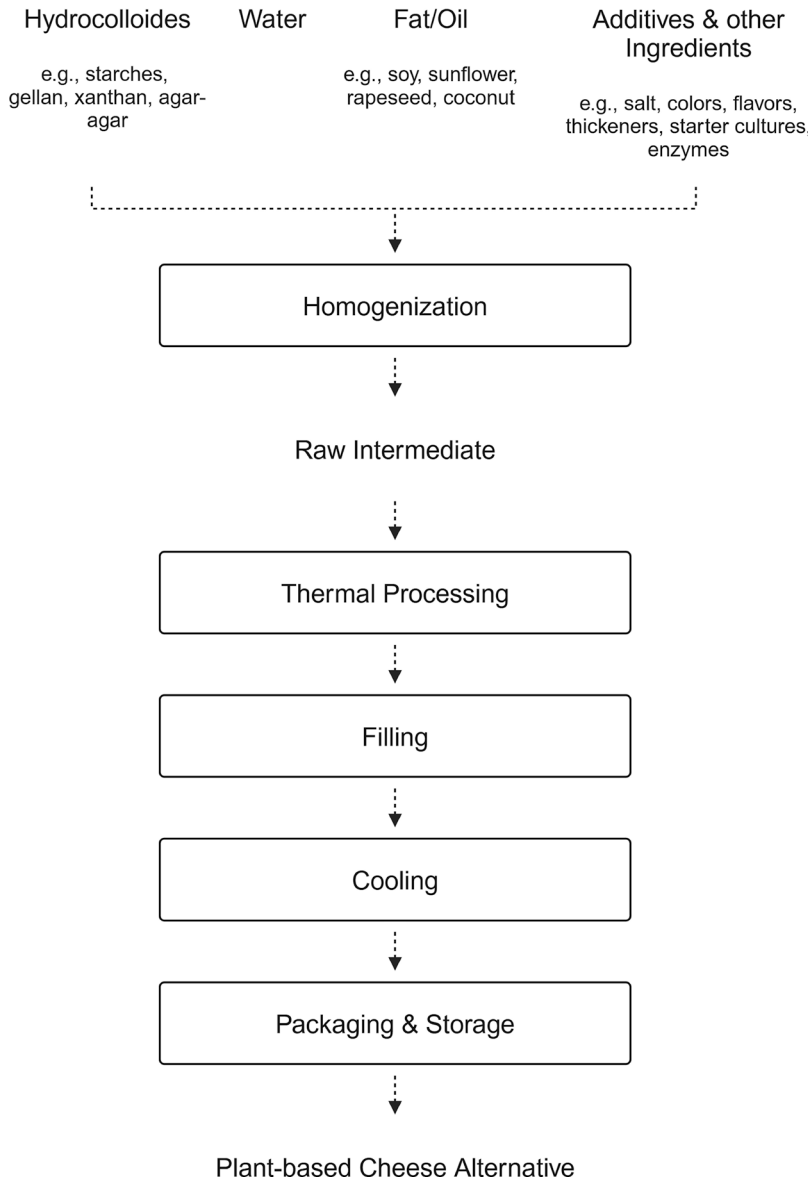


Fig. 21.11 General production flowchart of a plant-based cheese alternative using the "Carbohydrate-based Emulsification method". (Created in ► https://BioRender.com)

with the other ingredients, e.g. water, oil, flavours, colours, salts and other additives, to form an oil-in-water emulsion using high shear. This leads to a narrow particle size distribution and a homogeneous and stable product. Heating causes the hydrocolloids to form a network, which solidifies into cheese-like products during cooling in moulds. Products are then packaged and stored, typically under refrigeration conditions. In the protein-based emulsification approach, proteins are the main structure formation components, and processing steps vary depending on the type of proteins used (Fig. 21.12). Processing steps can include filtration, separation, cooling, ripening, forming or cutting (McClements and Grossmann 2022).

Tissue Disruption Method

This method is schematically shown in Fig. 21.13, and whole raw materials, such as soy, pea, lupin, oat or nuts, are first processed as described above to yield a plant-based milk alternative. Cross-linking of proteins and carbohydrates in the plant-based milk drink can be induced thermally, by pH-shift, enzymatic cross-linking, or salting-out effects, as previously described. Depending on the gelation mechanism, different post-processing steps may be needed to make sure that matrices are firm enough, such as drying, salting or smoking (McClements and Grossmann 2022).

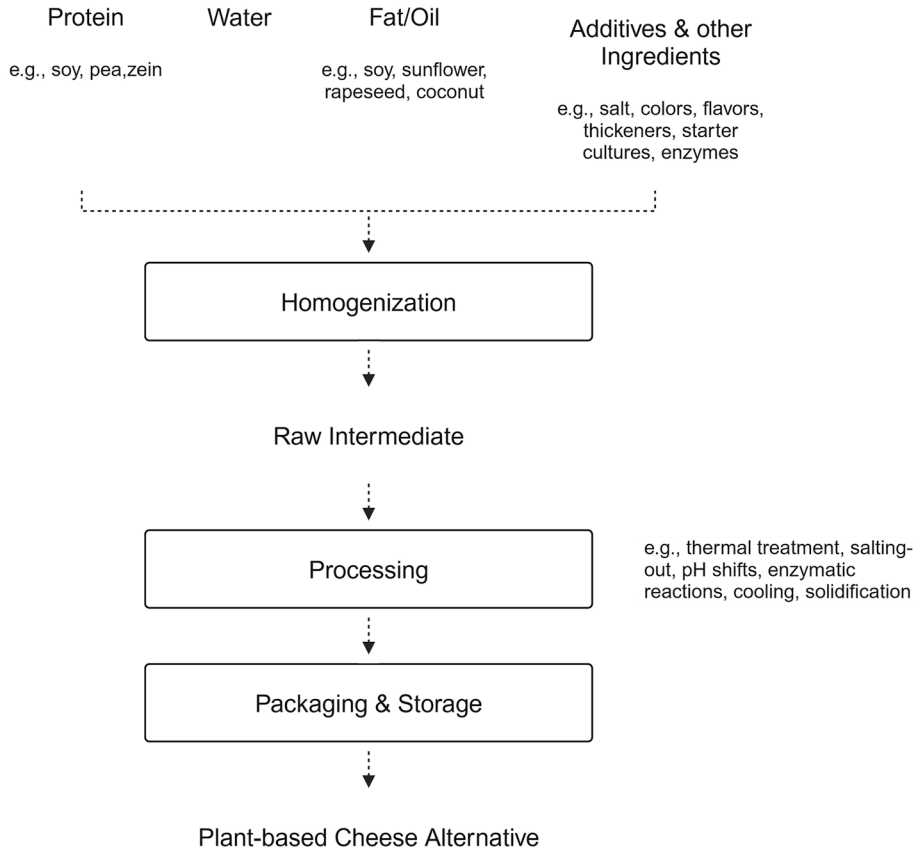


Fig. 21.12 General production flowchart of a plant-based cheese alternative using the 'Protein-based Emulsification method'. (Adapted from McClements and Grossmann 2022) (Created in ► https://BioRender.com)

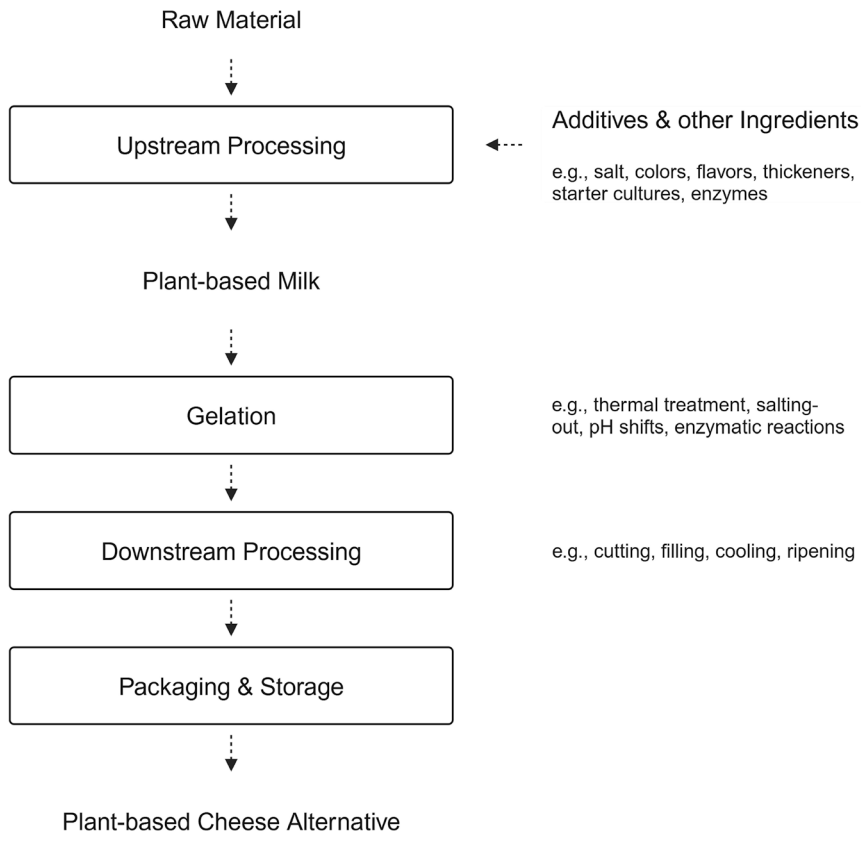


Fig. 21.13 General production flowchart of a plant-based cheese alternative using the 'Tissue disruption method'. (Adapted from McClements and Grossmann 2022) (Created in ► https://BioRender.com)

21.4 Concluding Remarks

There has been a lot of progress in the development of plant-based meat and dairy alternatives over the past 10 years, which is due to rising consumer demand with respect to vegan and vegetarian foods. Much of it has come from a better understanding of the functionality and properties, but also a decrease in price and an increase in the availability of alternative protein preparations obtained by efficient downstream processes. The transformation of such new raw materials into appealing foods has also been the target of investigations and has led to an understanding of how to design manufacturing processes that are flexible and scalable. One can expect further progress to be made in this field as new raw materials are developed and exploited. In this context, modern plant breeding techniques, or precision fermentation approaches, are likely to make a large number of new materials available for use in food design and manufacture. Research on not only protein but also fat structuring techniques is yielding matrices that have properties that closely resemble fat, meat or milk. However, there is still quite some work to be done on improving the nutritional profile of these products since they lack a number of important micronutrients, especially important vitamins and minerals.

Questions

1. What are the characteristics of plant-based proteins?
2. How does the extraction of plant-based proteins work?
3. What is needed for the production of meat alternatives?

Answers

1. Plant-based proteins are chains of amino acids that are linked together through a unique bond, the so-called "peptide" bond derived from plants. While milk and meat contain a lot of albumins and globulins, plants also contain significant amounts of glutelins and prolamins. Moreover, between different plants, there are substantial differences in the presence of each of these individual fractions.

   The main difference in composition of proteins between animal-derived and alternative proteins is based on their role within the originating organism. In plants, proteins often have a simple nitrogen storage function, providing nitrogen to the budding plant, while in animals, they must bind calcium and vitamins (such as in milk) to foster growth of the young animal or provide motility (such as in meat) to mammals.
2. Generally, four steps are carried out to obtain protein concentrates, isolates or meals:
   (a) The tissue is mechanically disrupted using mills or homogenizers that apply high mechanical stresses, thereby disrupting cellular structures. This leads to the enclosed proteins becoming accessible to solvents such as water.
   (b) Then, proteins can then be solubilized, facilitating a subsequent separation from all other compounds. Particularly, the prolamin and glutelin fractions are not water-soluble, and environmental conditions must therefore be changed to allow insoluble protein complexes to dissociate and go in solution. Temperature, pH, ionic strength, and conductivity are altered by heating or cooling, adding salts, acids or bases, or alcohols to accomplish this. Once in solution, the remaining cellular fragments (e.g. starch kernels, cell walls, fat droplets) can be separated by filtration, sedimentation or centrifugation.
   (c) The protein solution is typically again treated with acids or bases and/or the temperature is changed such that proteins fall out of solution, facilitating again a filtration, sedimentation or centrifugation. The proteins are then present in the filter cake or sediment, often at concentrations of 40–50%.
   (d) A spray drying or vacuum drying process may finally yield powders that have protein contents of well over 80%. Alternatively, membrane separation processes are increasingly used to separate proteins from small molecular weight compounds, eliminating the need to first precipitate the proteins. For medical or personal care applications or if enzymes are needed for catalytic processes, a final gel filtration or ion exchange chromatography may be applied. For food science purposes though, this last step is often omitted since it adds substantially to the costs of the obtained protein preparation.
3. To produce meat alternatives, the following are needed:
   (a) ***Binding agents***. Binders are an essential ingredient to form meat product analogues bringing together individual structural elements such as protein fibres and fat particles and also enhancing the consistency of products. To achieve this, binders have a high affinity for water or fat and oil, and through their association with these compounds improve gelling, thickening, and emulsion stability.
   (b) ***Micronutrients.*** Some minerals and vitamins are low or missing in vegan and/or vegetarian diets. Vitamin B12 (Cobalamine) is found only in foods of animal origin in amounts that are sufficient to ensure an adequate supply of the vitamin. Individuals who adhere to an exclusively plant-based diet (vegan) or consume

only minimal quantities of animal products are required to take a vitamin B12 supplement (McClements 2023). The estimated value for an adequate intake for adults is 4.0 µg per day. In addition to vitamin B12 and iodine, a vegan diet requires adequate amounts of essential amino acids, long-chain n-3 fatty acids, vitamin D, riboflavin, calcium, iron, zinc, selenium and vitamin A. These elements are regarded as potentially critical as they are often low in many analogue products (Klug et al. 2024).

(c) ***Colouring agents***. Colorants are required to imitate meat colour or the curing colour of sausages. Caramel colour, curcumin (yellow) (E100), betanin or beet juice extract, carotenoids (yellow-red) (E160, E 161, E 164) such as carotene (E 160a), canthaxanthin (E 161g) and lycopene (E160d, oil-soluble), carotenoid-rich extracts such as paprika oleoresins (E160c), annatto seed extracts (E160b), carrot extract or lycopene-rich extracts from tomatoes can be used for this purpose.

(d) ***Proteins:*** A wide variety of proteins are utilized, whether in the form of low- and high-protein flours (~10–50% protein), concentrates (~50–70%), or isolates (from 80% to ≥90%) (Loveday 2020). They exert a significant influence on the binding of water and oil, the stability of dispersions and the solidification of the matrix. Besides the named plant proteins, sunflower, canola, hemp, chickpea, oat, wheat, linseed, lupine, fava bean proteins and others have been used for the production of meat alternatives. Gluten in particular is often used as a binder, resulting in a notable improvement of the texture. The majority of plant proteins exhibit a higher denaturation and gelling temperature than their meat protein counterpart, typically ranging from 70 to 90 °C. For example, pea proteins gel and denature between 75 and 79 °C, which is substantially higher than those required for meat proteins.

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Transforming Bio-Based Sidestreams and Raw Materials into Food Ingredients

Mario Jekle, Jannika Dombrowski, Sandra Renz, and Margit Jekle

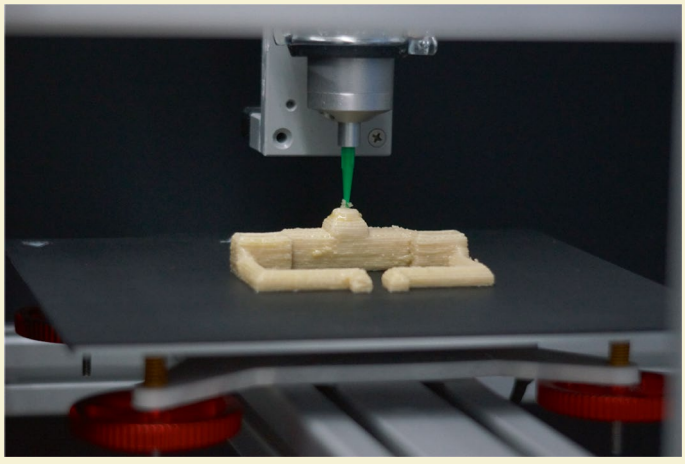


Fig. 22.0 Transforming bio-based sidestreams and raw materials into food ingredients. (© Universität Hohenheim, Dorothea Elsner) (► https://doi.org/10.1007/000-hv3)

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The transformation of bio-based sidestreams and raw materials into food ingredients represents a crucial step in the promotion of a sustainable circular economy within the framework of a food-first approach. From this perspective, the utilisation of sidestreams from the food and agricultural industries is intended to optimise the value of residual streams and minimise food loss and waste. By employing a range of processing techniques, including dry fractionation and wet extraction, it is possible to isolate and refine valuable components such as proteins, fibres and bioactive compounds for conversion into safe and high-quality food ingredients. This approach not only contributes to the sustainable utilisation of resources but also offers new avenues for the development of functional foods with enhanced nutritional properties. The chapter begins with an overview of potential sidestreams in the food sector and for the food sector as a whole. It is essential to recognise that only safe food can be subjected to further processing. Consequently, the evaluation of food sidestreams in terms of food safety and nutritional content is addressed in accordance with this premise. This chapter places particular emphasis on the fractionation and extraction procedures, which are of crucial importance in ensuring the quality and accessibility of these ingredients for food applications. Technological innovations also play a pivotal role in optimising the efficiency and cost-effectiveness of transformation processes. Finally, use cases, such as Brewers' spent grain and others, are presented to illustrate the integration and discussion of the acquired knowledge.

Learning Objectives

After studying this chapter, you will…

- …be able to describe possible food sidestreams (see ► Sect. 22.1).
- …be able to define food safety and nutrient value of sidestreams (see ► Sect. 22.2).
- …be able to describe the advantages and limitations of dry fractionation (see ► Sect. 22.2).
- …be able to explain the purpose of milling as a pre-treatment step (see ► Sect. 22.2).
- …be able to describe different approaches of raw material pre-processing (see ► Sect. 22.2).
- …be able to describe and delimit different separation techniques (see ► Sect. 22.3).
- …be able to give examples of the use of sidestreams on an industrial scale (see ► Sect. 22.4).
- …be able to estimate the economic value of sidestream exploitation (see ► Sect. 22.4).
- …be able to elaborate on the overall potential of upcycling for the food sectors (see ► Sect. 22.5).

22.1 Sidestreams in the Food Sector and for the Food Sector

It is estimated that approximately one-third of the food produced for human consumption worldwide is lost or wasted, which equates to approximately 1.3 billion tonnes per year (Gustavsson et al. 2011). Halving this food loss and waste would reduce greenhouse gas emissions from the food sector by 8% (Swannell 2024).

The following processes are identified as the most significant contributors to food loss and waste (FLW) within the food supply chain (Papargyropoulou et al. 2014):

1. Harvesting: e.g. leftover crops in the field, pests, suboptimal timing of harvest, loss in food quality.
2. Post-harvest: e.g. poor transport infrastructure, spoilage, deterioration, pests, disease, spillage, contaminations.
3. Food production and packing: e.g.:
   - Primary processing: cleaning, drying, sieving, milling, grinding.
   - Secondary processing: mixing, cooking, frying, molding etc.
   - Packing: damage due to inappropriate packaging, grain spillage from sacks due to rodent attack by rodents.

4. Distribution: e.g. damage during transport, spoilage, losses caused by lack of cooling/cold storage.
5. Consumer level (household, food services (restaurants, hospitality sector, cafes), institutions (education institutions)): e.g. over-buying, plate scrapings, surplus food cooked, poor storage/stock management in homes, indicated by exceeding shelf-life

It follows that a considerable proportion of the resources employed are generated unnecessarily, resulting in the emission of greater quantities of greenhouse gases than would otherwise be the case. In light of this, a primary objective of the United Nations is to reduce global food waste, thereby facilitating the transition to more sustainable production and consumption patterns by 2030 (United Nations 2015). As the global economy transitions towards a more circular and sustainable model, the food sector is facing the urgent need for innovative technologies. The objective is to optimise the utilisation of food resources to reduce their associated environmental impact and ensure the continued provision of food for the growing global population. Definitions of the key terminology are provided below for reference.

The term ***food loss*** is defined as the reduction in the quantity of agricultural, forestry and fishery products that were intended for human consumption but were not consumed.

The causes of food losses are numerous and can be attributed to inefficiencies within the food system. These losses occur at various stages of the food supply chain, including production, post-harvest and processing (Parfitt et al. 2010; FAO 2011).

The term ***food waste*** is used to describe food losses at the end of the food chain, specifically at the retail and consumer levels. These losses are influenced by the actions of retailers and consumers (Parfitt et al. 2010; FAO 2011).

Food waste or loss is restricted to products intended for human consumption, with the exclusion of feed and inedible portions of products. The term 'food loss and waste' refers to the mass of food lost or wasted in that part of the food chain that would have become edible products for human consumption. This approach distinguishes between 'planned' and 'unplanned' non-food applications, with the latter classified as losses (see Fig. ◘ 22.1).

Food that was originally intended for human consumption but subsequently falls out of the human food supply chain is regarded as ***food loss and waste (FLW)***, even if it is then directed to a non-food use (feed, bioenergy, etc.) (FAO 2011).

The terminology and definitions pertaining to the aforementioned topics are frequently contextualised and, as a consequence, may vary in their precise denotation across different reference sources. In light of this, the term 'food loss and waste' (FLW) is more frequently employed, as it encompasses both food losses and food waste.

Despite the fact that a considerable quantity of FLW is generated in developed countries at the household level, it is notable that 39% of the total volume is generated at the production level. These food processing sidestreams represent a significant portion of the total volume. They are currently unavailable on the market due to low demand or availabil-

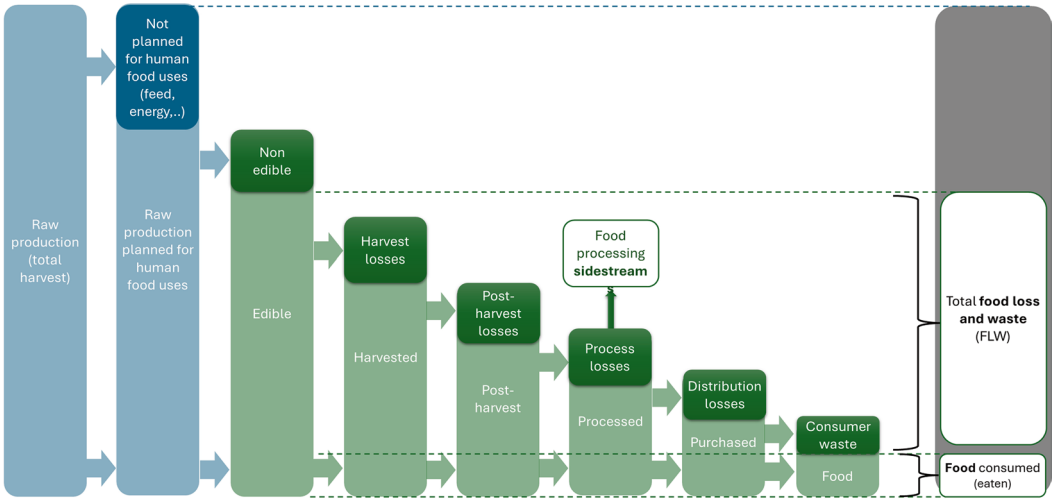


Fig. 22.1 Food loss and waste (FLW) along the food chain (unscaled). Raw agricultural production is divided into food and non-food. These are then further subdivided into edible and non-edible parts of the products. The total amount of FLW is the sum of losses and waste of edible food items that were originally intended for human consumption. The data presented here are based on food balance sheets as used by the FAO (FAO 2011) and described in other works (SIK 2011; HLPE 2014)

ity, food safety concerns (such as biological and chemical contaminants) and processing challenges. Despite the potential for reintegration into human nutrition, the comparatively low utilisation indicates a need for further research (Roth et al. 2019; Mirabella et al. 2014).

> ***(Food processing) sidestreams*** (also referred to as *co-products* or *by-products*) are generated during the production of intermediate products or marketable products across all sectors of the food production industry. While they are potentially edible, they are not currently available as final edible products on the market (Roth et al. 2019; Ladakis et al. 2020).

Despite the continued presence of highly valuable nutrients in these sidestreams, they are frequently used as fertilisers, substrate for biogas production, production substrates or, at best, as animal feed. This is due to their current inedibility for human consumption (Raak et al. 2017).

One illustrative example is brewer's spent grain, which was previously utilised as animal feed and is now being increasingly transformed into novel food ingredients. This phenomenon can be attributed to the compositional characteristics of such sidestreams derived from food processing, rendering them a compelling resource for further processing (also see ▶ Chap. 12 and use case III in ▶ Sect. 22.4.2). These include proteins, dietary fibres, lipids and valuable minor compounds such as antioxidants, vitamins, minerals and other bioactive compounds. These ingredients are associated with functional and nutritional properties that enable the development of nutritious food ingredients, nutraceuticals and functional food products. The amount of sidestreams used in the final product depends on the raw materials used and the desired final product.

22.1.1 Food Processing Sidestreams

The origin of sidestreams is diverse, with cereals, fruits and vegetables representing the primary sources (Porter et al. 2016). The following section presents a discussion of relevant sources of sidestreams:

22.1.1.1 Cereal Products

Cereal is a dietary staple in nearly all regions of the world and remains the most efficient source of energy for human consumption, thus making it an ideal ingredient for this purpose. In less economically developed regions, where food is scarce and protein is not affordable, cereal-based foods constitute the basis of the human diet.

Bran is a cereal-based sidestream resulting from the production of fine flour. Bran is a rich source of dietary fibre and can be incorporated into baked goods and breakfast cereals to enhance their nutritional profile. Moreover, functional fibre can be extracted from bran. Germ is a further cereal sidestream created during the production of flour products and is rich in vitamins, minerals and lipids. Brewer's spent grain is a sidestream created during brewing and is rich in protein and fibre (see Use Case III, ► Sect. 22.4.3). It has a distinct impact on the sensory properties of enriched foods, necessitating further processing steps.

22.1.1.2 Fruits, Vegetables and Tubers

Sidestreams derived from plant sources, including fruits, vegetables and tubers, offer a promising and versatile source of numerous valuable and nutritionally relevant compounds. These include phenolic compounds, carotenoids and specific carbohydrate polymers, such as lignin, hemicelluloses and pectin. For more information, please refer to Use Case II, ► Sect. 22.4.2 below. The utilisation of phenols and carotenoids in fruit and vegetables as natural preservatives in the food sector represents an effective strategy for extending shelf life and inhibiting the formation of off-flavours (Galanakis 2012). Moreover, the processing of sidestreams derived from berries and other red fruits represents a substantial source of antioxidants, phenolic acids, flavonoids and polyphenols (Mirabella et al. 2014).

22.1.1.3 Oilseed Cake and Meal

Sidestreams from the production of olive oil and wine collectively represent up to 60% of the total raw material and contain substantial quantities of bioactive phytochemicals that can be used as ingredients in food, cosmetics and pharmaceuticals (Pleissner et al. 2016) (see Use Case I, ► Sect. 22.4.1).

22.1.1.4 Dairy Products

The dairy sector generates a considerable quantity of liquid sidestreams during the production of primary products such as milk, cheese, yoghurt and butter. These sidestreams include whey, milk permeates and skim milk. Extensive research on whey has led to its successful transformation from a sidestream into a valuable food ingredient (Galanakis 2012). In general, the dairy sector developed a broad range of solutions for an economically viable pathway of extracting, modifying and applying sidestreams for reintegration in human nutrition.

22.1.1.5 Meat/Animal Products

The potential meat sidestreams are diverse, including gelatin, collagen, enzymes, trace minerals and nitrogen (Pleissner et al. 2016).

22.1.2 Food Safety and Nutrient Content of Sidestreams

It is imperative to guarantee the continued viability of the sidestreams by ensuring their safety and, where possible, optimising their nutritional quality for human consumption. In terms of food safety, it is essential to guarantee that both microbiological and chemical aspects comply with the requisite standards. This represents a significant challenge for the valorisation of sidestreams. Potential contaminants are outlined below:

- **Microbial pathogens**

The microbial load is found to be significantly correlated with the moisture content of the raw materials. The relevant microbial contam-

inants are vegetative bacteria, bacterial endospores, moulds and yeasts, as well as pathogens such as *Listeria monocytogenes, Bacillus* spores, *Salmonella* and *Escherichia coli*. A number of factors have been identified as influencing the microbial load, but they have not yet been the subject of sufficient research. These factors include pre-processing, moisture content, composition, co-cultures and others. The most efficient strategy is either a rapid processing procedure following sidestream generation and/or a rapid drying process following generation.

Mycotoxins

Mycotoxins can originate from microbiological contamination of the sidestream or from contamination of the agricultural raw material during cultivation, harvesting and storage. Due to their high heat stability, it is crucial to prevent the formation of mycotoxins or to implement an effective detoxification strategy.

Heavy metals

The presence of cadmium, lead, mercury and arsenic in products may be attributed to the contamination of agricultural areas, with a subsequent concentration during processing. Given the potential for significant health risks, the most effective approach is a rigorous monitoring programme and the establishment of safety limits for the raw materials used.

Pesticides

These substances are generated as a byproduct of agricultural processes, particularly during the processing of raw materials and sidestreams. Pesticides present a range of specific risks and regulatory constraints, necessitating a differentiated assessment approach. In the case of water solubility, a potential mitigation strategy could involve washing.

It is also essential to consider the nutritional value of the sidestream before and after upcycling to ascertain its potential for value addition and economically viable applications. In addition to macronutrients, the interest in various micronutrients is well-founded, as previously stated. In the context of contaminants and nutritional value, it is also necessary to consider anti-nutritional factors (ANF). ANF are present in a number of agricultural raw materials and foods and inhibit or reduce the absorption of other nutrients by the human body. Common examples of ANF include protease inhibitors, saponins, phytic acids, lectins and oxalates. Several mitigation strategies are known and applied in traditional processes such as cooking/heating, soaking and fermentation.

The implementation of individually adapted and appropriate storage, handling/processing practices and a valid risk assessment, including measures for contaminants, is of critical importance for all sidestreams. It is particularly important to consider the processing practices, as they can exert an additional negative or positive impact on the nature and quantity of contaminants, either through further concentration or depletion. To this end, a series of processing steps have been developed with the objective of valorising and transforming sidestreams in a manner that secures food safety, enhances nutritional quality and ensures the high functionality of the resulting products. The most common and important concepts of these processes are described in the following section.

22.2 Valorisation of Sidestreams—Upcycling

It is important to note that sidestreams are not considered ready-to-eat food ingredients. Rather, they are typically subjected to refinement processes and modifications to render them suitable for use as foodstuffs. These processes are referred to as *upcycling* (for further details, please see ► Chap. 12). The introduction of strategies for transforming sidestreams into edible food ingredients provides the food sector with a valuable opportunity to reduce food losses, optimise resource use, contribute to environmental sustainability by reducing the overall carbon footprint and, ultimately, ensure food security. Furthermore, the valorisation of sidestreams offers economic advan-

tages by reducing dependencies on primary materials, lowering production costs and creating new business opportunities in the food sector.

The following section presents an overview of the most significant processes for valorisation. It begins with an initial focus on dry fractionation methods and separation techniques, primarily targeting macronutrients. This is followed by potential supplementary extraction methods designed to concentrate macro- and micronutrients. The aforementioned processes are not exclusive to food processing sidestreams; they are also applicable to agricultural sidestreams and bio-based raw materials in general. However, approaches to modify the functional properties of sidestreams for additional design purposes are beyond the scope of this discussion and can be found in earlier sections.

22.2.1 Dry Fractionation

The term *dry fractionation* is typically used to describe solvent-free separation technologies to produce protein-, starch- and fibre-enriched products from bio-based (food) sidestreams and raw materials, whereby the native structure and function of the target compounds are largely preserved. It is considered very sustainable as it requires fewer processing steps than conventional wet fractionation, and the energy-intensive drying is omitted (Assatory et al. 2019). For instance, protein extraction by wet fractionation requires about 15 times more energy per kg of protein recovered than dry fractionation (Allotey et al. 2024). The main drawbacks of dry fractionation are the relatively low yield and purity that are achieved. This goes hand in hand with the presence of other compounds, which affect the nutrition, functionality and quality of the products.

The target compounds for enrichment by dry fractionation depend on the composition of the raw material. Pulses such as peas, faba beans, lentils, chickpeas and lupins, while primarily recognised as sources of starch and fibre, also contain significant amounts of protein (i.e. ~20–40%) and have been identified as valuable sources of protein to meet the growing demand for nutritious food (Fernando 2021). Sidestreams from oil extraction (e.g. soybean or rapeseed meal) naturally contain relatively high amounts of protein (i.e. ~30–50%), making them well-suited for producing protein-enriched ingredients (also see use cases). Wheat or oat bran, sidestreams from cereal processing (dry milling), are rich in fibres and are therefore ideal to obtain fibre-enriched fractions such as arabinoxylan or β-glucan (Assatory et al. 2019). Though not the focus of this chapter, it is worth mentioning that the term dry fractionation is also used to designate the modification of the chemical (e.g. iodine value) and physical (e.g. melting point) properties of multi-component solid fats (e.g. palm oil or coconut oil) by means of melt crystallisation.

The dry fractionation of bio-based sidestreams and raw materials typically involves two principal processing stages: *pre-treatment* or upstream processing and *separation* (see ◘ Fig. 22.2). These stages will be explained in greater detail in the following sections.

22.2.1.1 Pre-treatment

Pre-treatment is essential for improving the efficiency of the subsequent separation process. The most common pre-treatment techniques (also referred to as pre-processing) include dehulling, defatting and/or milling, which may be employed in conjunction with thermal techniques (see ◘ Fig. 22.2). Consequently, the separation efficiency is augmented, and the quality of the product in terms of nutrition, food safety and functional properties is also enhanced.

> ***Separation efficiency or yield*** refers to the ratio of the content of the target compound in the feed entering the separator to its concentration in the resulting product.

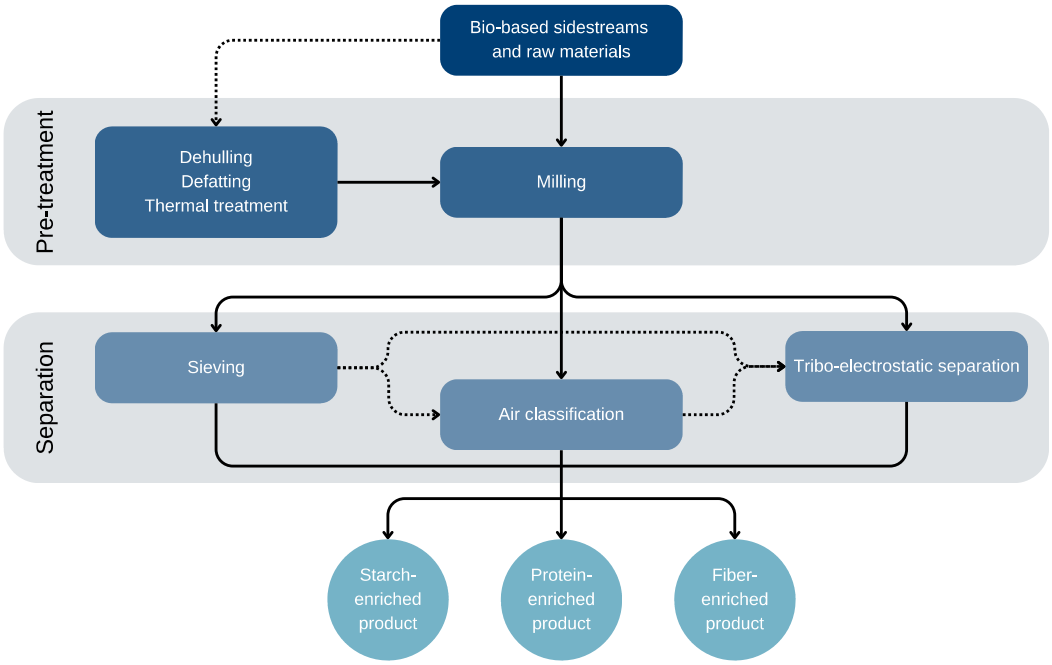


Fig. 22.2 Overview of dry fractionation techniques, including pre-treatment and separation methods. The separation techniques can be employed individually or in a series

> ***Purity*** refers to the relative concentration of the target compound in the resulting product.

Dehulling is an optional pre-treatment step prior to milling. Its main goal is to enhance the quality of the raw material, for instance, by reducing the content of certain anti-nutritional substances (e.g. phenolics and tannins) and compounds contributing to bitterness. Eventually, this may be accompanied by an improvement of colour, resulting in a lighter tint (Stone et al. 2024). Regarding the actual separation, the effect of dehulling on the yield of target compounds appears to be raw material-dependent but overall, rather limited (Saldanha do Carmo et al. 2022).

For oil-rich raw materials such as soybeans, rapeseed or sunflower kernels, *defatting* is crucial to enable subsequent dry fractionation. In a nutshell, it reduces agglomeration and increases particle flowability. Typically, the defatting step occurs as part of the primary value creation, which is the extraction of vegetable oil. Thereby, the meal or press cake occurs as a sidestream. Defatting can be achieved through various techniques, with organic solvents (e.g. butane or hexane) and mechanical extraction (e.g. cold pressing) being the most common. Mechanical defatting presents a safe, mild and sustainable option, though it is less effective than solvent extraction (Nde and Foncha 2020). Further defatting methods comprise the use of supercritical fluids such as carbon dioxide (CO_2) or aqueous extraction.

Milling is a key pre-processing step as it facilitates the physical detachment of cellular microstructures, such as starch granules, proteosomes and bran fragments. This process ultimately aims to create differences in particle size, enabling the separation of the primary compounds, such as starch granules and protein fragments (Schutyser and van der

Goot 2011). According to Assatory et al. (2019), the milling result is affected by several factors, including the hardness of the raw material, its chemical composition and the starch granule size. Milling techniques explored upstream to dry fractionation include pin milling, hammer milling, attrition milling, jet milling and impact milling. Often, multiple milling steps are utilised, such as pre-milling with a pin mill, followed by fine milling with an impact mill or pre-milling with a hammer mill, followed by pin milling.

Unlike wet or liquid fractionation, classic dry fractionation does not involve any kill-step (e.g. pasteurisation), wherefore high microbial load, presence of antinutritional substances (e.g. trypsin inhibitors, saponins) as well as endogenous enzyme activity (e.g. lipoxygenases) impart the risk to deteriorate product quality (e.g. food safety, digestibility or sensory properties).

Thermal pre-processing methods such as conventional hot air drying, fluidised bed drying or more novel technologies like radio frequency or infrared radiation treatment, have the advantage of efficiently counteracting these factors, enabling higher quality products.

22.2.2 Separation Techniques

The following section provides an in-depth examination of the three principal technologies employed in the actual separation step to enrich target compounds: sieving, air classification and tribo-electrostatic separation. Given that the separation principles of these methods differ, it is essential to have a detailed understanding of the physicochemical properties of the bio-based raw material or side-stream and the compounds to be fractionated. It should be noted that these methods can be used individually or in combination (see Fig. 22.2).

Dry *sieving* is a simple and inexpensive method with a long history of use in the food sector to separate fines from larger particles. For example, it can be used to fractionate fibre-rich husks from the starch-rich endosperm in malted barley kernels (Wetterauw et al. 2023). This method takes advantage of particle size differences, whereby the preferred range is from 40 µm to about 125 mm. Below 40 µm, the separation efficiency is significantly reduced, and air classification or electrostatic separation may be better alternatives. For sieving, either several single sieves with increasing mesh size or sieve stacks with decreasing mesh size can be used. The main drawbacks of sieving are the relatively low yield and purity. Additionally, sieves are typically prone to clogging (Schutyser and van der Goot 2011).

Separation by *air classification* is based on differences in particle size and density. It is a viable alternative to sieving in the particle size range of 2–60 µm and particularly below 40 µm, where sieving becomes ineffective. Centrifugal and gravitational forces induced by air in a classifier chamber enable the fractionation of the feed into a fine and a coarse fraction. The cut point for separation is influenced by the air classifier wheel speed and the airflow rate. For example, the optimum cut point for the separation of starch granules and protein fragments is around 15–22 µm, which is below the size of most starch granules. Shifting the cut point towards a lower particle size can result in higher purity but also lower yield (Rempel et al. 2019).

Tribo-electrostatic separation is used when the target compounds to be separated are not significantly different in particle size or density. The principle of this relatively new technique is based on differences in electrostatic charging of particles induced by particle-particle and particle-wall interactions. For instance, C- and N- side chains of protein molecules are more ionizable and have a higher proton affinity than starch fractions, allowing them to acquire a higher positive charge (Tabtabaei et al. 2016). By contrast, fibre fractions acquire a negative charge. Charged fractions can be separated in a transversal electrostatic field, with protein and starch molecules accumulating at the anode, while the fibre fraction will be concentrated at the cathode (Wang et al. 2016). Hence, tribo-electrostatic separation is well suited to obtain fibre-enriched products. An important parameter during tribo-electrostatic separation to

maximise purity is the charge-to-mass ratio. This, in turn, depends on the particle collision number, the wall material and the charging time of the particles (Yang et al. 2022).

22.3 Extraction Methods

22.3.1 General Extraction Methods

This section outlines general (liquid) extraction techniques and supplementary methods for the isolation and purification of compounds from bio-based raw materials and food processing sidestreams. Due to the large number of processes and new developments, this list may not necessarily be exhaustive. Dry fractionation primarily concentrates macronutrients, including protein, starch and fibre. Subsequent extraction methods are designed to further concentrate these compounds, as well as minor compounds such as bioactive substances and liquid and volatile compounds, including flavour-active compounds and alcohols. It is essential to comprehend these methods and their relevance within the context of environmental concerns and sustainability to establish a more comprehensive and holistic value chain.

22.3.2 Distillation

Distillation is one of the oldest techniques for ingredient fractionation, with the first evidence of its use dating back more than 5500 years (Schlosser 2011). Distillation is a thermal separation process, where compounds are separated based on boiling point differences. While it was originally introduced to extract flavours for perfumes or medical purposes, it has quickly been exploited to produce alcoholic spirits. First, raw materials are suspended in a suitable solvent, fermented or steamed. The mixtures are gradually heated until the boiling point of the target component is reached, causing it to vaporise. The gas is led through the distillation apparatus and ultimately condensed at a cooler and collected. Distillation is straightforward and delivers reproducible results with high purity if the boiling point(s) of target compound(s) are exactly known, and processes are controlled accordingly. Nowadays, multi-stage, fractional and vacuum distillation apparatus are used, which enable the purification and concentration of various volatile compounds from one starting material.

22.3.2.1 Solvent Extraction

Solvent extraction is widely employed in the food sector to isolate compounds such as lipids, essential oils, natural colourants, flavours, fragrances, antioxidants and other bioactive substances. It is a liquid-liquid or solid-liquid separation technique, depending on the composition of the starting material and the respective solvent used. The latter may be polar (i.e. water, ethanol, acids, bases), non-polar (i.e. hexane, oil, supercritical CO_2) or a mixture thereof. The fundamental principle relies on solubility differences of macro- and micronutrients in these solvents, enabling the selective concentration and separation of target compounds. During extraction, the solvent or solvent mixture penetrates the raw material, thereby dissolving the target compound(s). After sufficient contact time, the mixture undergoes filtration, centrifugation or decantation to remove the solid residues or non-miscible phases, resulting in one or more solutions containing the dissolved compound(s).

Solvent extraction is a highly versatile technique, as the choice of solvent allows for the sequential extraction of a range of compounds from a single raw material. Furthermore, the variables of temperature, agitation, pressure and extraction time can be systematically adjusted to enhance the yield, influence compound solubility and safeguard its functionality. Consequently, liquid–liquid and solid–liquid extraction are integral to numerous industrially scaled processes within the food sector. After extraction, the dissolved substances can be recovered through a variety of methods, including induced precipitation, which can be achieved through a pH shift or a change in ion concentration for protein precipitation.

However, conventional extraction (CE) technologies require large amounts of solvents and lengthy treatment times, making them less cost-effective and more time-consuming. Consequently, several assistance technologies have been developed to improve the extraction performance, which will be discussed in the following sections.

22.3.3 Assisted Extraction Methods

22.3.3.1 Supercritical CO_2 Assisted Extraction

Supercritical fluid technology is an environmentally friendly extraction method that produces high-quality products. Supercritical carbon dioxide ($SCCO_2$) is the most commonly used supercritical fluid, particularly in the food processing industry. Due to its low critical temperature, the thermal degradation of natural products and the subsequent formation of undesirable compounds are minimised or avoided. Furthermore, it is non-toxic, inexpensive and generally non-reactive, making it an ideal choice for use in food, nutraceutical and pharmaceutical products. Due to its lipophilic nature, $SCCO_2$ has become the most suitable and promising substitute for hexane-type solvents in food processing, enabling many new processes and products. The first industrial-scale processes to be successfully implemented were the decaffeination of coffee beans (Zosel 1982) and the extraction of hops, spices and herbs (Srinivasan 2014).

22.3.3.2 Ultrasound-Assisted Extraction

Ultrasound is defined as sound that is above the range of human hearing, so above 20 kHz (up to 1 GHz). This technique is used for a variety of food processing purposes, including drying, emulsification and homogenisation, inactivation of microorganisms and enzymes and especially extraction (Misra et al. 2018).

During ultrasound application, cavitation bubbles can form. The collapse of those bubbles leads to cell disintegration near cell walls, increasing solvent entry into the cells and intensifying mass transfer (Barba et al. 2015; Misra et al. 2018; Tiwari 2015). Furthermore, the shockwave has the potential to promote swelling and hydration, which may result in larger pores in the plant cell wall and structural changes in plant tissue (Zhu et al. 2017). Ultrasonication offers several significant advantages over conventional supporting methods, such as heating, making it an attractive option for many applications. These advantages include lower energy consumption, a shorter treatment time, lower solvent consumption, a higher yield and the benefit of being a non-thermal technology, which is safer for operators and has a lower impact on the environment (Chemat et al. 2017) (Roselló-Soto et al. 2015). Due to its ability to enhance extraction processes, ultrasound can be used to extract food ingredients from various plant-based foods and sidestreams, making it a valuable tool for the food sector.

22.3.3.3 Microwave-Assisted Extraction

Over the past two decades, microwaves (MW) have become a crucial processing tool in the field of food science and technology. It is a common technology in laboratories and industries for a variety of applications, including (i) microwave-assisted extraction (MAE), (ii) food drying, as well as (iii) enzyme inhibition and inactivation, microorganism inactivation and sidestream processing (Bouras et al. 2015; Deng et al. 2015). From a scientific perspective, microwave radiation falls within the category of non-ionising radiation, with frequencies ranging from 300 MHz to 300 GHz (Barba et al. 2015; Roselló-Soto et al. 2016). MW generates heat due to its interaction with polar cellular compounds. The internal heating process results in the accelerated deterioration of materials and increased diffusion of target compounds. It is important to note that some compounds cannot withstand high temperatures, whereas the low-polarity solvents can. In such an MAE, the heat would disrupt the cell walls by expansion and facilitate the diffusion of the desired valuable compounds from the cell material towards the cooler solvent. MAE is a versatile

technique that can be applied to a range of plant materials to obtain valuable bioactive compounds, offering a valuable tool for the extraction of these compounds. (Juana M. Carbonell-Capella et al. 2017; Périno et al. 2016). MAE is a preferred option due to the shortened treatment time, significant increase in yield, lower energy consumption and reduced solvent use. Consequently, MAE represents an environmentally friendly solution for processing (Chemat et al. 2017).

22.3.3.4 Enzyme-Assisted Extraction

Various enzymes are used to optimise the extraction process through hydrolysis, which effectively dissolves the plant cell wall matrix, thereby increasing extraction yield. The enzymatic reactions facilitate the disintegration of the cell wall and enhance cell permeability, thereby optimising the extraction process. The success of enzyme-assisted extraction (EAE) is dependent on several factors, including reaction time, type and concentration of enzyme used, temperature, pH value and the particle size of the plant material (Poojary et al. 2017; Roselló-Soto et al. 2016). EAE is usually combined with conventional chemical solvent extraction, reducing the amount of solvent required and shortening the extraction time in line with green extraction approaches. However, one of the main challenges associated with EAE is the cost of enzymes, which can be relatively high for large quantities of raw material.

22.3.3.5 Pulsed Electric Field

Pulsed electric field (PEF) serves as a substitute or amplifier for conventional extraction methods, such as liquid–liquid extractions. The treatment involves the application of electric fields ranging from 100–300 V/cm to 20–80 kV/cm in short pulses lasting from microseconds (μs) to milliseconds (ms). The treated products have to be placed between two electrodes (Calleja-Gómez et al. 2024). Several factors influence the efficiency of PEF, including electric field strength, pulse duration and length, number of pulses, as well as food product-specific parameters like conductivity and pH. PEFs permeabilize bio membranes, thereby modifying and optimising extraction kinetics. It has been applied for extraction of several compounds in the food sector, particularly from food sidestreams and plant tissues. There are studies and applications for proteins, polyphenols and antioxidants, where PEF was used as a pre-treatment before extraction techniques. It is considered a non-thermal process and can thus be applied to thermolabile compounds.

22.4 Use Cases for Upcycling to Food Ingredients

This section highlights three exemplary use cases to provide a comprehensive understanding of the market value, the technological approaches and functional application potential of upcycling sidestreams, and to demonstrate how they contribute to the development of a more resilient bioeconomy.

22.4.1 Use Case I: Oil Cake Meal

Soybeans, sunflowers and canola (rapeseed) rank among the five most important oilseed varieties worldwide, with a total annual production of more than 500 million tons per year (Statista 2024). Oil cake meal, also known as oilseed pomace or cake, refers to the sidestream that remains after the production of vegetable oils (see Fig. 22.3), representing up to 60% of the original raw material. Oil cake meal is traditionally used for feed purposes due to its high protein and fibre content and good digestibility. The economic value of soybean meal was around 59.2 billion US$ in 2021, which exceeded soybean oil (52 billion US$) as the primary food product derived from soybeans (Bundele 2023). Recently, oil cake pomace has gained considerable interest for human nutrition due to the rising demand for plant-based protein sources and fibre-enriched diets. Most industrial processes rely on patents from the 1950s, which first introduced methods for purifying proteins from soybean cake. In short, multiple extraction methods are used that rely on solubility differ-

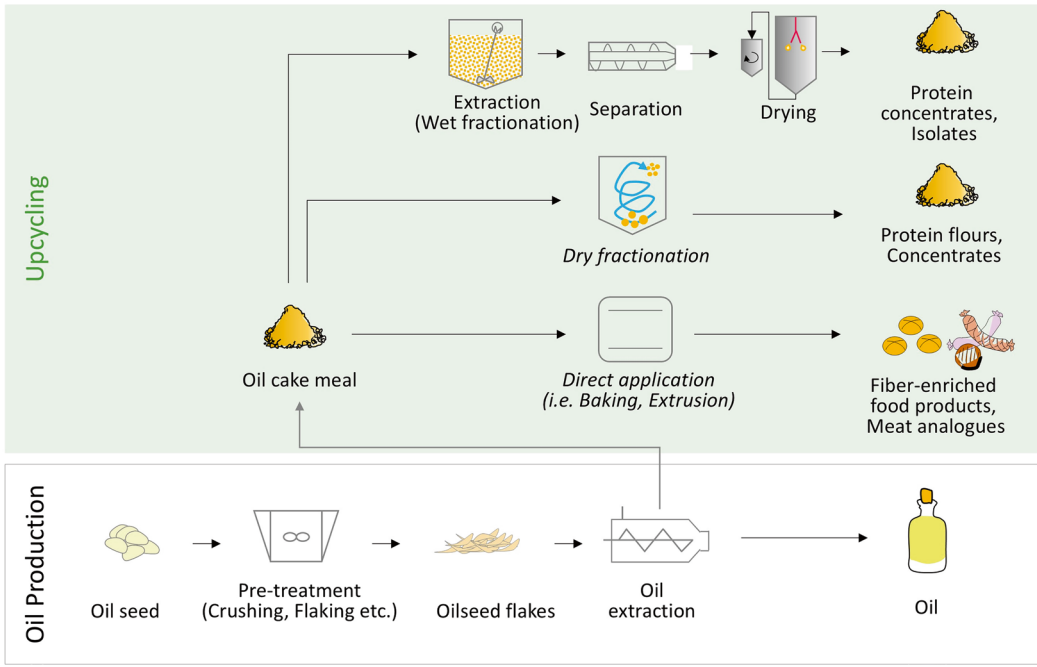


Fig. 22.3 Use case of oil cake meal—schematic of model for oil production from plant-based oil seeds and the upcycling of the sidestream oil pomace, also known as oilseed pomace or cake

ences of proteins, carbohydrates and lipids in acid–water or base–water mixtures (see ▶ Sect. 22.2). Over the past few decades, industrial processes using the so-called 'wet fractionation' method have been substantially optimised and adapted to extract proteins not only from soy, but also from various other oilseed varieties, including sunflower, canola, peanuts, pumpkin and flaxseed. Sustainability concerns and the need for new protein functionalities have further boosted innovation for alternative extraction processes. One such approach is 'dry fractionation' (see ▶ Sect. 22.2), which separates milled protein-rich raw materials by size and density, eliminating the need for solvents and subsequent drying (see Fig. 22.3).

Technological advances in wet and other fractionation techniques have led to the development of a wide range of commercial protein flours, concentrates and isolates. In 2022, the market size of soy, canola and sunflower proteins was 7700 million USD, 60 million USD and 50 million USD, respectively, with an estimated compound annual growth rate of 7–14% until 2027 (Grand View Research 2023; Markets and Markets). They are tailored for specific food purposes, which depend on the origin, composition and applied processing techniques. Protein flours are generally used as thickeners or for fibre-fortification in cereals, bakery and pastry or in meat analogues. Concentrates and isolates are applied to increase the protein content or to provide functionality (e.g. emulsification) in meat and dairy alternatives, sports nutrition and beverages. There are also further non-food valorisation attempts for oil cake meals. This may include the production of bioethanol or biofuels via microbial fermentation or the manufacture of biopolymers for eco-friendly packaging materials. In summary, the potential of oil cake meals is versatile.

Many processes for their transformation and use in food ingredients and products have already been established, and the markets show considerable growth potential.

22.4.2 Use Case II: Fruit Pomace and Peels

Citrus fruits, bananas, apples and grapes are among the most consumed fruits globally. According to the Food and Agriculture Organization (FAO) of the United Nations, 179 million tons of bananas/plantains, 162 million tons of citrus fruits, 96 million tons of apples and 75 million tons of grapes are produced globally each year (Pereira Gonzatto and Scherer Santos 2023). While some are consumed fresh, a large portion is processed into canned fruit, purees or beverages, with pomace and peels emerging as significant sidestreams (see Fig. 22.4). For example, processing apples to produce juice or cider results in 25–35% of pomace depending on the process and variety used. As one-fifth of the overall production is used for beverages, approximately 4 million tons of apple pomace are produced per year. The disposal of these fruit sidestreams presents challenges due to their high volume, moisture and organic matter content. Additionally, fruit pomace and peels are rapidly decomposed microbially, leading to significant methane emissions—a greenhouse gas that is 28 times more potent than CO_2 (Mirabella et al. 2014). However, the exploitation of fruit pomace and peels has a long history in the food sector due to their functional carbohydrates: pectins. Pectins are complex structural polysaccharides that serve as gelling agents, thickeners and stabilisers. They are essential for producing jams, marmalades and fruit preparations for confectionery and beverages. The industrial extraction of pectins from citrus peels (85.5%) and apple pomace (14.0%) is the most common, as they contain 25–35% and 10–15% of pectins in dry matter, respectively. In the extraction process, fruit pomace and peels are dried, milled, boiled and filtered. The pectins can then be precipitated via water miscible alcohols such as ethanol or isopropanol and standardised by a simple drying and milling process.

As methods evolve, recent advancements have introduced enzymatic, microwave, ultrasound, subcritical water and CO_2-assisted extraction. These innovations have not only resulted in higher yields and pectins with modified functionality, but have also expanded the range of fruits used, including mango, pineapple, figs and tomato. Furthermore, adopting sustainable extraction methods has

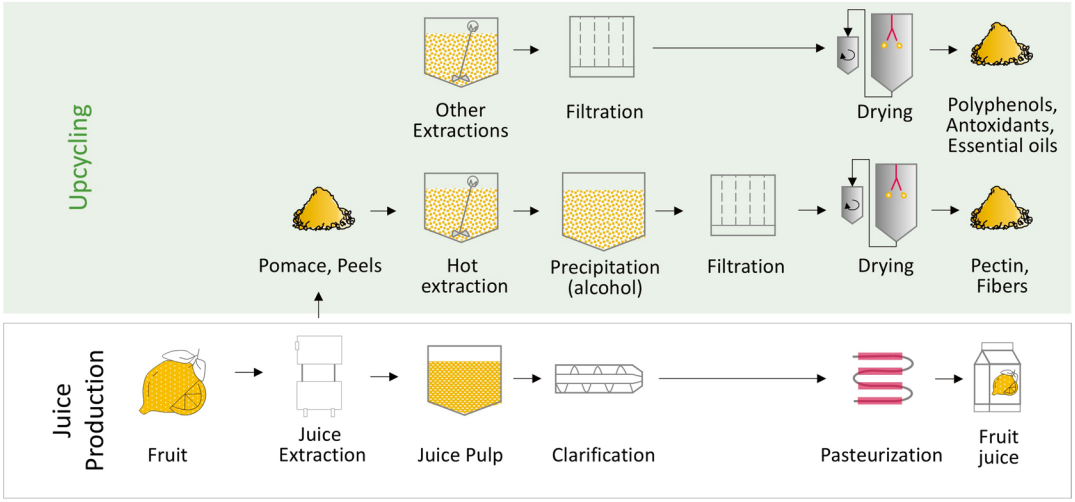


Fig. 22.4 Use case juice production—schematic of a model process for juice production and the upcycling of the sidestream pomace and peels

substantially reduced the environmental footprint of pectin production. The global market size of pectins was 1170 million USD in 2023 (Imarc Group 2023), along with an estimated yearly market growth potential of more than 7%, driven by the growing demand for natural ingredients and clean labelling. Besides pectins, dietary fibres, polyphenols, antioxidants and essential oils are further compounds of fruit pomace and peels (Sandhu et al. 2021). Despite their high value for functional foods, nutraceuticals, pharmaceuticals and cosmetics, industrial plants for extracting these compounds are still rare, mainly due to high investment costs and concerns regarding the high amount of energy, chemicals and solvents necessary.

In conclusion, fruit pomace and peels are among the most commonly valorised sidestreams in pectin extraction. Industrial upcycling offers a symbiotic solution that simultaneously addresses ecological and economic challenges.

22.4.3 Use Case III: Brewer's Spent Grain (BSG)

Beer is one of the oldest processed beverages, with an estimated global production of two billion hectoliters per year (Huber 2024). During its production, three sidestreams emerge at different time points during manufacture: brewer's spent grain (BSG), hot trub and brewer's yeast (see Fig. 22.5). One liter of beer results in approximately 0.2 kg of BSG, making it the largest sidestream, with a global production of around 40 billion kg annually. Like oil cake meals, BSG is traditionally used for animal feed. Breweries typically collaborate with regional farmers, who pick up the BSG on a schedule aligned with beer production, as it is highly susceptible to microbial spoilage. In the last decade, however, various attempts have been made to scale up the standardisation and use of BSG for food purposes due to its high nutritional value. BSG contains around 70% fibre and

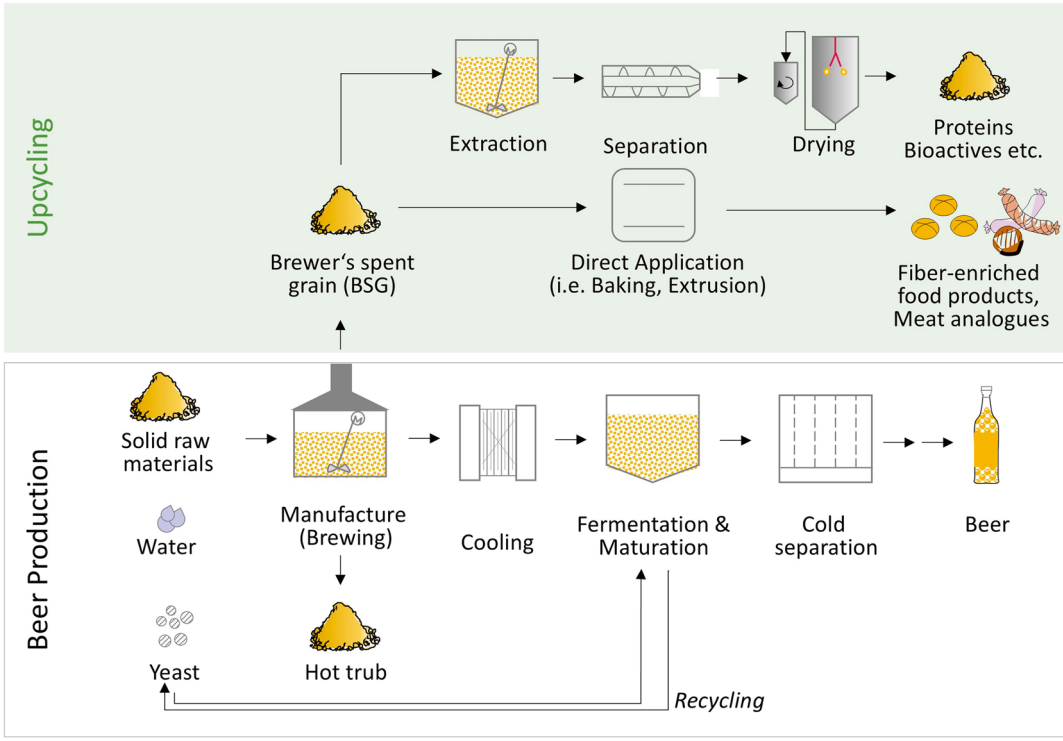


Fig. 22.5 Use case Brewer's spent grain (BSG)—schematic of a model process for beer production and the upcycling of the sidestream Brewer's spent grain

20% protein on a dry matter basis, as well as considerable amounts of phenols, minerals and vitamins (Mitri et al. 2022). It is commonly used as a dried, milled powder in breads and pastries (pizza dough, bagels, muffins, doughnuts, brownies), snack products (cookies, bars) and cereals (Rachwał et al. 2020). Additionally, BSG is used to enrich extrudate premixes for the manufacture of meat analogues or for biodegradable packaging materials. It can be subjected to various extraction methods followed by separation and drying to obtain proteins, as well as bioactives such as prebiotics, phenols and saponins. Furthermore, BSG has been recently proposed for precision fermentation purposes. It can be used as media to grow bacteria, yeasts or fungi to produce proteins (alternative meat products), organic acids (L-lactic and citric acid), sugar alcohols (xylitol) and enzymes (cellulases, hemicellulases).

However, scalability, high energy and logistic costs for pre-processing currently limit its exploitation to smaller scale plants. Besides, its composition may vary depending on the grains and methodologies used for beer manufacture, which limits a reproducible quality. For all solutions, the original taste as well as its techno-functional properties due to the high fibre content must be considered when implementing BSG in a food matrix.

BSG thus represents a versatile sidestream with promising market prospects, especially as technological innovations to integrate BSG standardisation into existing beer manufacturing lines are expedited.

22.4.4 Use Cases: Conclusion

The upcycling of oilseed meals, fruit pomace and peels and BSG highlights the significant potential for transforming bio-based sidestreams and raw materials into value-streams. Embracing upcycling practices also contributes to sustainable development goals, enhances resource efficiency, prevents negative ecological effects and fosters innovation. This aligns with increasing consumer demands for sustainable and ethically produced food products and cleaner labels. These aspects will pave the way for a transition from a linear to a circular economy and the thorough exploitation of natural resources.

22.5 Challenges and Prospects

Technological advancement is essential for developing cost-effective and scalable processing methods that preserve the nutritional and functional qualities of upcycled products. Economic obstacles, including the establishment of reliable supply chains and the achievement of competitive pricing in comparison to conventional materials, must be overcome.

In addition, many other challenges at different levels must be addressed:

- From a material perspective, fluctuations in the availability of sidestreams are influenced by seasonal variations and market demands. The quality of these sidestreams is also variable, due to the heterogeneous nature of the raw materials and the impact of environmental factors and annual effects. Contaminants and food safety concerns are additional considerations, with microbiological loads and chemical contaminants being of particular importance.
- From an acceptance perspective, the economic viability of specific sidestream transformations must be considered, including consumer acceptance of novel ingredients, which in turn determines the success of new products and markets.
- From a technological perspective, the focus has been on developing cost-effective upcycling processes and reducing process complexity and to enhance scalability.
- From a legislative perspective, there is considerable variation across different countries regarding the use of sidestreams and the regulatory limitations that apply to this practice. Furthermore, the E.U. level novel foods regulation also has an impact on this issue.

In order to advance the adoption of circular (bio-)economy solutions within the agricultural and food sector, it is imperative to develop a market for upcycled products

derived from sidestreams, including engaging with consumers. It can be reasonably assumed that consumer involvement will lead to a high level of acceptance and willingness to purchase these products. (Chiaraluce et al. 2021).

Questions

1. What are the main opportunities and challenges related to the upcycling of sidestreams?
2. Discuss the potential and key benefits of upcycling agricultural and processing sidestreams for the food sector.
3. Identify and elaborate on the main technological, economic and environmental challenges that hinder a thorough exploitation of resources.
4. Name technologies and processes used for upcycling.
5. In your factory for oat flakes, oat bran occurs as small-volume sidestream. Oat bran is rich in starch, fibre and protein, but also contains a relevant amount of fat. Please describe a possible route for the fractionation and valorisation of oat bran constituents.

Answers

1. Opportunities—Waste reduction, new/additional sources of valuable (macro-) nutrients to enhance nutrition and functionality of food products, including meat and dairy alternatives

   Challenges—Food safety and regulatory constraints, cost efficiency of upcycling, processability of less refined ingredients (e.g. flours, protein concentrates).
2. Holistic use of natural resources, less food waste, ecological benefits (less soil pollution, lower greenhouse gas emissions), direct valorisation in the food value chain, boosting food innovation.
3. Logistic problems (transportation of sidestreams to the respective processor, otherwise: need to integrate into existing food manufacturing processes or regional partnerships), standardisation (reproducible quantities and qualities), competing valorising for food or feed purposes, must be economically feasible and beneficial.
4. Wet fractionation, dry fractionation, hot extraction, drying.
5. Dry fractionation could be a suitable approach. As a first step, defatting would be advisable to ease subsequent milling and ensure a high separation efficiency. The milling conditions should be adapted to ensure a size difference between starch granules and protein fragments. Hence, during a first separation step using air classification, starch- and protein-enriched fractions could be obtained with fibre being present in both fractions. A second separation step using tribo-electrostatic separation could allow fractionation of fibre and thus, allow increasing the purity of starch and protein fractions as well as obtain a fibre-enriched ingredient.

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Extraction of Fibres for Non-food Applications

Manuel Clauss and Hermann Dauser



Fig. 23.0 Extraction of fibres for non-food applications. (© Lina Mayorga-Duarte) (► https://doi.org/10.1007/000-hv4)

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23

This chapter examines the basics of natural plant-based fibres, their uses and extraction methods. Natural fibres can be classified into five categories: wood fibres, stem/bast fibres, leaf fibres, seed fibres and fibres from grasses and other annual plants. Their properties depend on the biomass of origin and the extraction methods applied. We also describe one of the main industrial extraction processes, the hydrothermal fibre production process, which involves biomass pressure processing followed by steam explosion treatment.

Learning Objectives

After studying this chapter, you will…

- …be able to describe which type of fibre originates from which type of biomass (see ► Sect. 23.1).
- …be able to explain why different fibre extraction methods are required (see ► Sect. 23.2).
- …be able to explain the principles of the hydrothermal fibre production process (see ► Sects. 23.2 and 23.3).

Natural plant-based fibres are a major component of plant-based biomass and offer a broad variety of applications. In combination with competitive and scalable extraction and purification processes, their extraction plays a crucial role in the bioeconomy and the valorisation of plant-based biomass in general. Since natural plant-based fibres typically provide products with an inherently low CO_2 footprint and, at the same time, high biodegradability, they are key to a sustainable bio-based economy, meet legal regulatory requirements, and can potentially replace fossil-based products.

Firstly, it is very important to differentiate between the terms 'natural' and 'plant-based' fibres at the very beginning. By definition, natural fibres include animal fibres (e.g. silk, hair) and mineral-based fibres (e.g. asbestos). We also distinguish natural plant-based fibres from biopolymeric fibres that have been manufactured by an industrial process based on natural polymers (e.g. regenerated cellulose, viscose 'Lyocell'). In addition, the term 'fibre' is widely used in the context of 'dietary fibre', which implies food-grade substances. Unless otherwise stated, dietary fibre and fibre for food applications are excluded from this overview.

> A ***fibre*** itself is technically defined as a substance that is significantly longer than it is wide and is characterised by increased orientation and tensile strength (and other properties) in the direction (length) of the fibre.

23.1 Types, Composition, Structure and Sources of Fibres

Natural fibres are becoming increasingly important as they offer a sustainable alternative to synthetic products and are biodegradable. From a historical point of view, synthetic fibres are a relatively new product that emerged in the course of the last century with the development of the chemical industry around synthetic polymers. Prior to this, the nature of polymers and their products was poorly understood, and natural fibres had a 'monopoly'.

There are many different types of plant fibres, each with its own unique characteristics, that can be used for various purposes, including textiles, paper, rope, nonwovens, composites, etc. In general, plant fibres can be divided into five categories: wood fibres, stem/bast fibres, leaf fibres, seed fibres and fibres from grasses and other annual plants. ◘ Table 23.1 gives a brief overview of non-wood and non-seed fibres.

Unlike synthetic fibres, natural plant-based fibres are usually a multi-component product. They do not consist of one single class of component, but of a mixture with

Table 23.1 Origins of different types of non-wood and non-seed fibre crops

Fibre crops	Biomass crops	By-products and residues

Bast fibres:
- Hemp
- Flax
- Jute
- Kenaf
- Nettles
…
Leaf fibres:
- Sisal
- Abaca
- Yucca
…
	Fibres derived from sweet grasses:
	- Bamboo
	- Giant reed
	- Miscanthus
	- Napier grass
	- Reed canary grass
	- Reed
	…
		Fibres derived from:
		- Cereal straw:
		  – Wheat
		  – Rye
		  – Barley
		  – Rice
		  – Maize
		- Straw from oilseed crops
		- Bagasse
		- Palm oil empty fruit bunches
		…

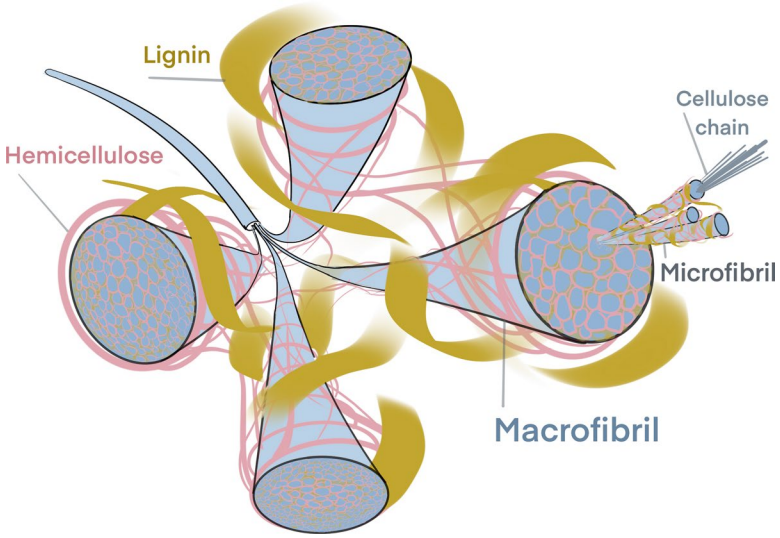


Fig. 23.1 Structure of natural plant-based fibres

cellulose, hemicellulose and lignin as the main constituents. The outermost layer of fibre is usually made up of a layer of lignin, the inner layer of hemicellulose, and the innermost layer of cellulose (Fig. 23.1). The specific composition depends on the plant from which they are extracted and the extraction process (Fig. 23.2).

The 'fibre' itself (milli- to micro-metre range) consists of fibrils and microfibrils (micro- to nanometre range) that originate from crystalline molecular cellulose chains (less than nanometre range).

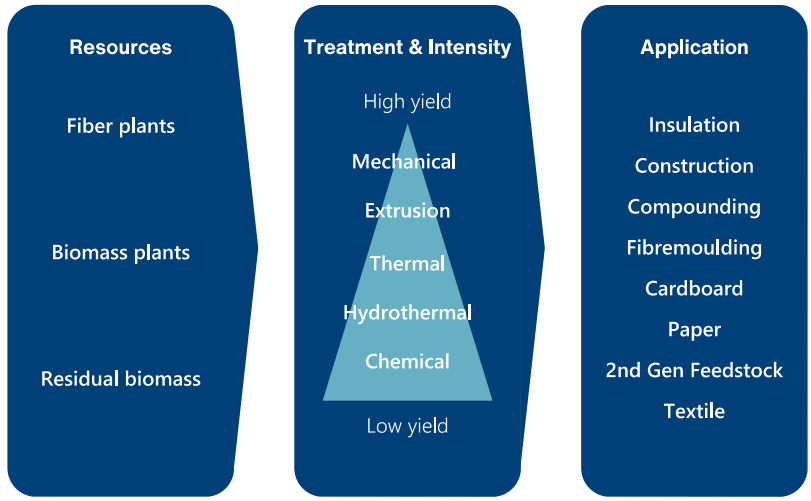


Fig. 23.2 Fibre extraction processes applied to different bio-based resources, providing material for various types of applications

23.2 Extraction Processes

There are various methods of fibre extraction, but the method is selected mainly for or as a consequence of (Mohankumar et al. 2021):

1. The plant and the type of fibre to be extracted.
2. The application and its requirements.
3. The market and the product demand (in order to be able to produce the required quantities and be competitive).

The main industrial extraction processes applied include mechanical, thermal, hydrothermal and chemical and extrusion processes (Fig. 23.2).

An example of fibre extraction for paper production is given in ▶ Sect. 17.2.3, where a pulp mill is used as an example of a traditional biorefinery. The 'traditional' main objective of fibre extraction is to obtain the maximum quantity of extracted fibre of the highest possible quality for further processing. Fibre extraction technology produces fibres that are bound together in the form of strands. The production of technical fibres involves the destruction of the stem or other part of the plant containing fibre-bearing tissues (e.g. sisal is produced from leaves).

In the context of the bioeconomy, maximising the yield of a single product is not necessarily the 'ultimate' goal. In a functioning biorefinery model, various products and processes are highly interconnected and all product streams need to be valorised—not least to make the whole concept competitive. It is important to note that not every process is sufficiently scalable per se. The success of such a model depends on the flexibility to respond to fluctuations in feedstock quality, demand and selling prices. Overall, it can be said that multi-product approaches will be required in future. These include the utilisation of waste streams in revenue-generating products without thermal combustion and CO_2 generation.

Such a multi-product approach can also support the reindustrialisation of hemp. This high-quality bast fibre, usually used for textiles, makes up only 20–30% of the dry mass of the stem. There are significant lignin-rich parts, such as shives, that remain unused despite their potential to provide short fibres. However, the resulting high-quality hemp fibre would need to be sold at a market price that is too high for many applications. The price could potentially be lowered by 'subsidising' it through the valorisation of side products.

The shift from a sole focus on a single product to a portfolio of many products in parallel requires process solutions that leave these side products 'intact'. This is why some of the pro-

cesses mentioned are attracting increasing attention, as is shown here by the example of the hydrothermal fibre production process.

Hydrothermal Fibre Production Process

The hydrothermal fibre production process involves high-pressure processing and steam explosion treatment of biomass.

Hydrothermal Biomass Processing

The main objective of the hydrothermal treatment is the thermal decomposition of biomass in a humid environment, i.e. either wet or moistened biomass is used or process water is applied in the form of steam. The different compounds of the plant-based lignocellulosic structures need to be separated by melting procedures.

Typical reaction parameters of such a treatment are:

1. Starting around 140 °C, hemicellulosic compounds are solubilised
2. Starting around 150 °C, lignin begins to melt from the fibre structures
3. Up to 180 °C, cellulose is only slightly affected, with no significant solubilisation

However, at temperature levels above 165 °C, inhibitors such as furfural and HMF can be expected to form, and at temperatures above 180 °C, undesired carbonisation reactions occur that degrade lignocellulose-based fibre structures. For fibre production, reaction temperatures below 180 °C are favourable, in contrast to other hydrothermal processes, e.g. in the ethanol industry, where higher temperature levels, even above 200 °C, are applied.

The optimum treatment temperature varies for each type of biomass. Typical temperature levels range from 150 to 180 °C. For wheat straw, for example, a suitable level is around 170 °C. The mild hydrothermal treatment of biomass does not lead to a complete decomposition of the raw material into its main constituents cellulose, hemicellulose and lignin. The resulting fibrous aggregates still contain significant amounts of each, as shown in Table 23.2.

Steam Explosion Treatment

Hydrothermal processing takes place at temperatures between 150 and 180 °C in a wet environment and is typically carried out in a steam cooker under saturated steam conditions, which means increased pressure is required. Table 23.3 shows the boiling point of water at different absolute pressures.

The wet biomass in the cooker is treated under boiling conditions at reference pressure and temperature, resulting in a significantly

Table 23.2 Composition of four biomass raw materials (range in %) and their hydrothermally produced fibres (average in %)

	Wheat straw		Rice straw		Corn stalk		Miscanthus	
	native	fibre	native	fibre	native	fibre	native	fibre
Cellulose	32–45	56.6	28–41	46.3	35–40	54.0	35–42	65.8
Hemicellulose	20–45	17.2	22–35	10.5	21–27	11.4	20–29	6.7
Lignin	11–26	9.5	14–22	11.9	17–20	11.2	16–19	13.4

Table 23.3 Specific data points from the saturated steam curve

Absolute pressure	bar	1	2	3	4	5	6	7	8	9	10
Boiling point (water)	°C	100	120	133	144	152	159	165	170	175	180

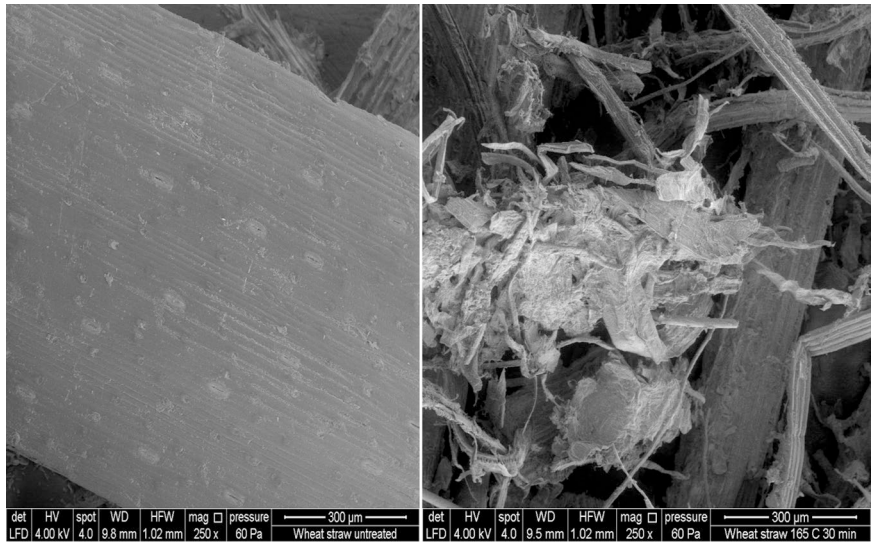


Fig. 23.3 SEM images of native and steam-exploded wheat straw. (BOKU University, Vienna (2015)

higher energy input compared to boiling conditions at ambient pressure. When the hydrothermally treated biomass is returned to normal pressure during media discharge, this excess energy is released and has to be immobilised.

During shock expansion, about 10–15% of the water in the wet medium spontaneously evaporates, creating multiple steam bubbles from water droplets with a volume expansion factor of around 1000. This physical reaction, known as steam explosion, produces enormous shear forces around and within the fibrous aggregates, resulting in a high degree of fibrillation and the formation of fibre surfaces with high binding potential including hydrogen bonding.

The functional quality of the fibres produced is strongly related to the original plant characteristics, which, despite optimised treatment conditions, lead to limitations in the 'fibres' applicability. Figure 23.3 shows wheat straw after steam explosion.

Biomass from grasses such as sugar cane, miscanthus and cereal straw can be expected to have good fibre properties. Bast fibre plants, such as hemp, flax and jute (see Table 23.1) have even better fibre properties. However, fibres from many other plants, including hemp shives, are only suitable for minor applications such as fibre moulding purposes.

23.3 Case Study: SteamFiber RSE Process of Fibers365 GmbH

An example of a successfully implemented hydrothermal fibre extraction technology is the SteamFiber process introduced by Fibers365 GmbH (Fig. 23.5). The core equipment of this technology is the SteamFiber Rapid Steam Expansion (RSE) system, which is a continuous hydrothermal process with a patented energy recovery system. The main process steps are described with reference to the schematic diagram in Fig. 23.4. These process steps are:

(a) Feedstock buffer and wetting chamber (addition of process water to chopped biomass).
(b) Pre-steaming reactor (preheating by condensation of flash steam in wetted feedstock).
(c) Pressure lock and feed tank (for batch feeding of biomass to the steam cooker).
(d) Pressure cooker (hydrothermal treatment of biomass).
(e) Flash tank and product storage (steam explosion process and flash steam separation).

The SteamFiber setup is designed to process agriculturally produced bales of annual crops

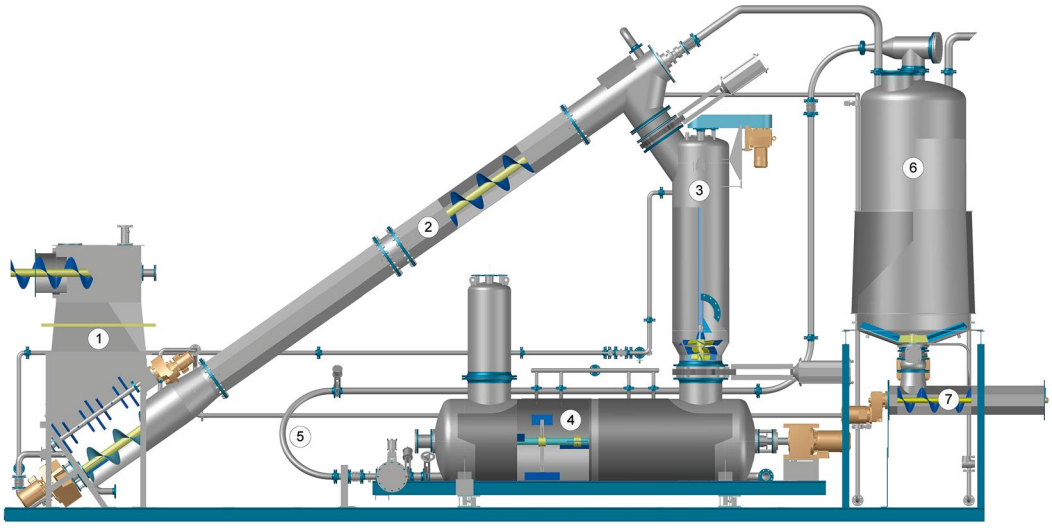


Fig. 23.4 Schematic diagram of the SteamFiber RSE system



Fig. 23.5 SteamFiber plant

or crop by-products with a typical capacity of 5000–10,000 t dry material per year. The plants are typically integrated into a regionally based agriculture, preferably including a biogas plant. The biogas plant fulfils an important purpose in a bioeconomically advanced setup. The liquid residues from the fibre extraction process, which contain about 40% of the original biomass, are digested in the biogas plant, and the biogas produced is converted into heat and electricity to cover the energy demand of the fibre extraction process. The remaining digestate, which contains well-digested organic residues with high humification potential and mineral fertiliser components, is returned to agricultural fields.

This concept incorporates regional aspects in raw material sourcing as well as advanced circular economy aspects, demonstrating the possibility of moving away from conventional, large-scale wood-based fibre/pulp production to a modular, on-farm biorefinery system capable of utilising residual biomass stream.

23

Questions

1. What is a fibre and how do synthetic fibres differ from natural fibres?
2. Why are different natural fibre extraction methods required?
3. What are the main steps in a hydrothermal fibre production process?

Answers

1. A 'fibre' itself is technically defined as a substance that is significantly longer than it is wide and is characterised by an increased orientation and tensile strength (and other properties) in the direction (length) of the fibre. Natural fibres are derived from plants or animals. Synthetic fibres are a relatively new product (first introduced in the twentieth century) and are produced by the chemical industry, often using fossil mineral oil as the raw material.
2. Plant fibres differ in their characteristics, for example, length and composition, depending on their origin, i.e. the plant or plant part from which they are derived. For this reason, they require different extraction methods. The differing applications of plant fibres, which require specific properties of the fibres, also make different extraction methods necessary.
3. The hydrothermal fibre production process involves biomass pressure processing in a first step, followed by steam explosion treatment in the second. In the first process, the biomass is broken down in a humid environment. This is followed by steam explosion, which results in a high degree of fibrillation and creates fibre surfaces with high binding potential, including hydrogen bonding.

Reference

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Bioenergy: Energy Derived from Biomass

Iris Lewandowski



Fig. 24.0 Bioenergy—energy derived from Biomass. (© Iris Lewandowski) (► https://doi.org/10.1007/000-hv5)

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Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/978-3-032-09098-0_24. The videos can be accessed individually by clicking the DOI link in the accompanying figure caption or by scanning this link with the SN More Media App.

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24

Biomass can be converted into various forms of bioenergy using thermal, chemical or biological processes. This chapter provides an overview of the main bioenergy pathways: combustion, gasification, pyrolysis, hydrothermal liquefaction, anaerobic digestion, fermentation and transesterification. These result in heat and power generation or biofuels. All types of biomass can be used to produce bioenergy, but they require different processing pathways. From an ethical point of view, nonedible, mostly lignocellulosic or residual/waste biomass should be the preferred feedstock. Bioenergy production can also be integrated into biorefinery processes.

Learning Objectives

After studying this chapter, you will…

- …be able to explain the difference between traditional and modern bioenergy pathways (see ► Sect. 24.1).
- …be able to describe the main technologies of modern bioenergy production (see ► Sect. 24.2).
- …be able to discuss the determinants of the greenhouse gas mitigation potentials of biofuel (see ► Sect. 24.3).

24.1 Traditional and Modern Bioenergy

Biomass has been traditionally used for energy production—for cooking (Fig. 24.1) and heating through combustion, mostly with low efficiency (Fig. 24.2). Today, we differentiate between this traditional use and modern uses of biomass.

In 2012, about 66% of bioenergy supply was traditional (Fig. 24.2), but this proportion is expected to decrease in future. Modern heat and power generation (for reasons of efficiency, preferably in combined production and in modern stoves) and transport biofuels are increasingly being used, and the bioenergy sector is growing.

While biomass was the main source of energy at the beginning of industrialization and in the days of the steam engine, bioenergy now accounts for only 8.04% of total energy supply, of which 7.3% is from traditional biomass use and 0.74% from liquid biofuels. The amount of energy produced from fossil resources such as coal, oil and gas is much higher (Fig. 24.3).

Modern bioenergy pathways range from direct combustion for heat and power genera-



Fig. 24.1 Children collecting firewood to be used for cooking and baking. (© Lena Winkler)

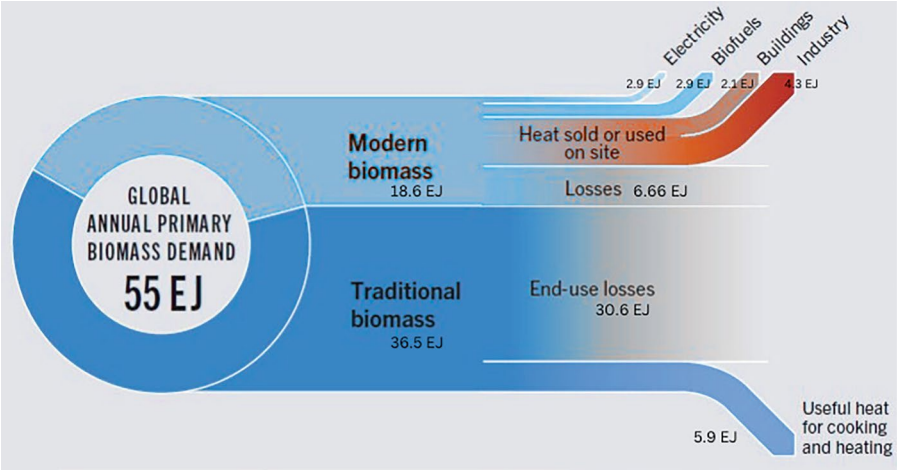


Fig. 24.2 Annual primary biomass demand. In traditional use of biomass for cooking and heating, a large proportion of the biomass energy is lost. Modern biomass uses are more energy-efficient and include electricity, heat and biofuel applications. (Author based on REN21 2013)

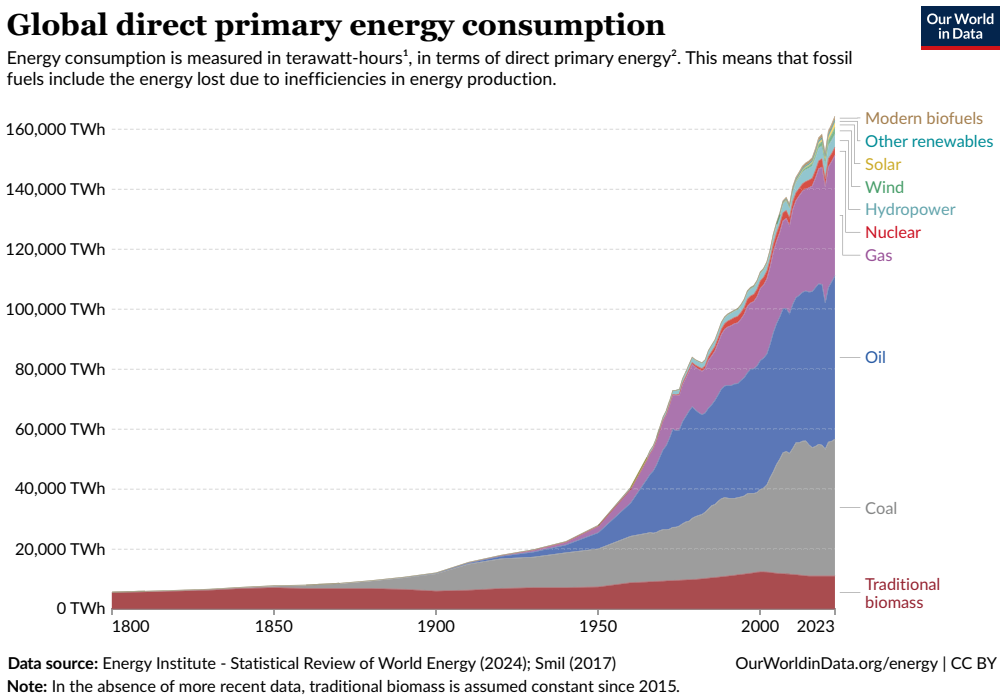


Fig. 24.3 Global direct primary energy consumption (TWh) since 1800. (© Our World in Data licensed under CC BY 4.0. (► https://creativecommons.org/licenses/by/4.0/). Data Source: Energy Institute—Statistical Review of World Energy (2024); Smil (2017))

tion to more advanced processes, such as gasification, pyrolysis, fermentation, hydrothermal liquefaction, anaerobic digestion and transesterification, through which energy from biomass can be harnessed to produce electricity, heat and transportation fuels.

24.2 Technologies of Modern Bioenergy Production

Modern bioenergy pathways differ in terms of the technologies applied, the characteristics of the feedstock, and the resulting products. The following sections provide a systematic description of the processes involved.

■ Combustion

In combustion, biomass is burned in the presence of oxygen to produce heat, which can be used directly for heating or to generate electricity through a steam turbine. The process efficiency varies depending on the technology applied, and is typically between 20% and 40% for electricity generation. When biomass is co-fired in modern coal power plants, efficiencies of up to 45% can be achieved. Typical feedstocks include wood and wood residues such as logs, chips, sawdust and forestry residues, as well as agricultural residues such as straw, corn stover and husks. Dedicated energy crops, e.g. miscanthus, switch grass and short rotation coppice (willow, poplar) are also used. These should preferably have a low moisture and ash content and be processed into uniform particles for a continuous combustion process.

■ Gasification

In the process of gasification (See Chap. 19), biomass is converted into a synthesis gas (syngas) containing carbon monoxide, hydrogen and carbon dioxide by partial oxidation at high temperatures (800–1000 °C) without combustion, using a controlled amount of oxygen and/or steam. This results in a mixture of hydrogen, carbon monoxide and other gases that can be used to produce electricity and heat or converted into biofuels such as methanol or synthetic natural gas. Another product is biochar, a carbon-rich solid that can be used as a soil amendment, a carbon sink (for example, by mixing into soil or adding to building materials) or for material applications such as wastewater filters. The process efficiency can reach up to 50% for electricity production and 70–80% when used for combined heat and power (CHP). Typical feedstocks are the same as for the combustion process and include wood, wood and agricultural residues, lignocellulosic energy crops and organic waste. These should preferably have a low moisture content and be processed into uniform particles for consistent gasification.

■ Pyrolysis

Pyrolysis (See Chap. 19) is the thermal decomposition of biomass in the absence of oxygen, resulting in bio-oil, syngas and biochar. The bio-oil can be upgraded to transport fuels or used directly for heat and power generation. The syngas and biochar can be used similarly to those produced by gasification (see description above). The yield of bio-oil ranges between 60% and 75% of the biomass input. The feedstocks used are the same as in the combustion and gasification processes. They must be free from contaminants, with dry feedstocks being preferred. For efficient conversion, they are typically processed into small, uniform particles.

■ Hydrothermal Liquefaction (HTL)

In the HTL process (See Chap. 19), biomass is converted into bio-crude (a petroleum-like substance) under high pressure and in a hot, pressurized water atmosphere for an appropriate period of time. The bio-crude can be upgraded to drop-in fuels such as gasoline (petrol), diesel and jet fuel. The aqueous phase contains dissolved organic matter that can be used to produce biogas. Wet biomass is converted without drying—the water in the biomass becomes the reaction medium. Feedstocks include food waste, sewage sludge, manure, agricultural and forestry residues, algae and aquatic plants.

Anaerobic Digestion

In anaerobic digestion (See Chap. 13), biomass is broken down by microorganisms in an oxygen-free environment, resulting in biogas and digestate. The biogas produced is a mixture of methane (CH_4) and carbon dioxide (CO_2) that can be used to generate heat and electricity or as a vehicle fuel. The methane content can reach 50–75%, with higher levels increasing the energy yield. The nutrient-rich biogas digestate is used in agricultural practice as an organic fertilizer. It can also serve as a feedstock for bio-based recycling fertilizers (see ▶ Chap. 14). Feedstocks with a high moisture content and easily degradable organic matter are ideal. These include animal manure, sewage sludge, food waste and agricultural residues. Typical energy crops grown specifically for biogas production are maize and grass, both processed to and stored as silage.

Fermentation

Fermentation (See Chap. 18) is the process by which sugars and starches from biomass (e.g. maize, sugarcane, cellulosic materials) are converted by microorganisms into ethanol. Bioethanol is a liquid biofuel used in internal combustion engines or blended with gasoline (petrol). Feedstocks include sugar crops, mainly sugarcane and sugar beet and starch crops such as maize, wheat and potatoes. Feedstocks rich in sugars, starches or cellulose can be easily converted to fermentable sugars. Cellulosic feedstocks require pre-treatment through enzymatic hydrolysis to break down the cellulose into fermentable sugars.

Transesterification

Transesterification involves replacing the alkyl functional groups in fats and oils from biomass (such as vegetable oil or animal fat) with methyl alcohol. The process is often catalysed by an acid or base catalyst. This chemical reaction with alcohol (usually methanol) produces biodiesel and glycerine. The biodiesel can be used in diesel engines or blended with petrodiesel. The by-product glycerine is used in various industrial applications, such as in the cosmetics and pharmaceutical industries. A high lipid content of the feedstock is essential for efficient conversion into biodiesel. Varying feedstock quality affects the transesterification process and quality of the final product.

In bioenergy production, the choice of feedstock is crucial as it influences the efficiency, cost and environmental impact of the process. Various bioenergy pathways have been optimized to suit specific types of biomass—from dry materials such as wood and agricultural residues to wet feedstocks including manure, sewage sludge, organic waste and algae, or for biomasses with specific components such as oil, starch or sugar, e.g. from dedicated energy crops. ◘ Figure 24.4 provides a simplified overview of the feedstocks and the conversion processes used to produce power, heat and liquid biofuels.

Biofuels are differentiated into first and second generation, or conventional and advanced biofuels. Conventional biofuels are biodiesel and ethanol produced from vegetable oil, starch and sugar. They are criticized for using edible biomass obtained from dedicated energy crops such as rapeseed, sugar cane and cereals. Advanced biofuels are those produced from lignocellulosic feedstocks. These can originate from agricultural and forestry residues, such as wheat straw, corn stover, bagasse and wood-based biomass. They can also stem from non-food crops (e.g. grasses, miscanthus, algae) or from industrial waste and residue streams. Their production processes apply advanced technologies, such as gasification, pyrolysis, hydrothermal liquefaction or enzymatic hydrolysis. They have lower CO_2 emissions or higher greenhouse gas (GHG) reduction potentials than conventional biofuels and have zero or low ILUC (= indirect land use change, see ▶ Sect. 28.4.2) impact.

Biofuel production has increased dramatically since the year 2000 (see ▶ Sect. 27.2.1, ◘ Fig. 27.4), with 34% being biodiesel and 66% ethanol (Statista 2024). Ethanol is mainly produced from coarse grains and sugar cane.

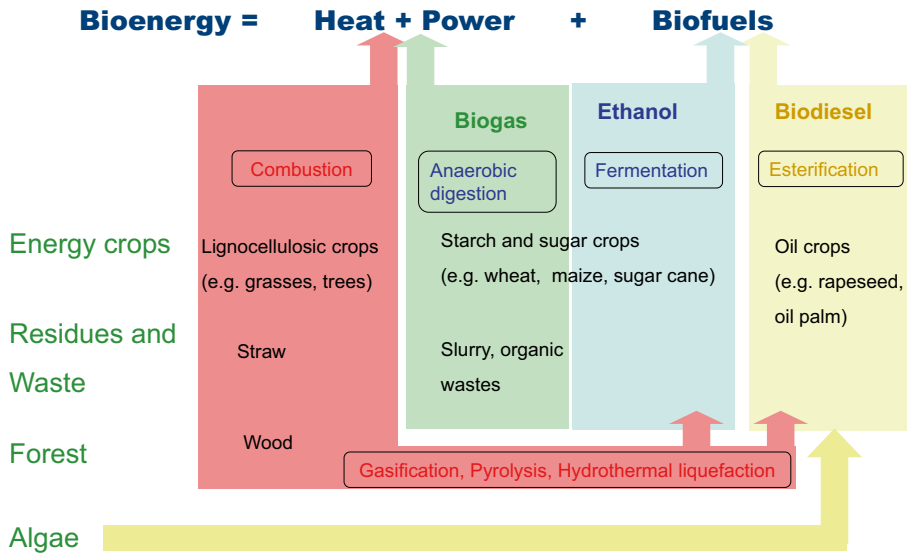


Fig. 24.4 Origins and characteristics of biomass for different conversion processes and bioenergy applications

Biodiesel is produced from fats and vegetable oils, predominantly rapeseed oil in temperate climates and palm oil in tropical regions. However, there are policies in place, particularly in Europe and the USA, that aim to ensure that an increasing proportion of biofuels are produced from residual biomass and wastes.

24.3 Sustainability Aspects

In Brazil, the global pioneer in bioethanol production, decades of political support have resulted in a competitive bioethanol production sector. In Europe, biofuel mandates and incentives for biomass and bioenergy production have been established (see ▶ Chaps. 27 and 28). Here, either large subsidies for biomass production or high taxes on fossil fuels are necessary to keep bioenergy on the market. Political support for bioenergy was legitimatized by expectations of economic development, in particular, additional income opportunities in rural areas, and by ecological benefits, especially climate change mitigation.

Bioenergy, and in particular liquid transportation biofuels, are increasingly being challenged because of their environmental impacts, failure to reduce GHG emissions to the expected amount and potential competition with food supply.

The GHG reduction potential of bioenergy depends on the amount of GHGs emitted during the production of the feedstock, including land use change impacts, and during processing. The so-called 'GHG mitigation potential' is calculated by subtracting the GHG emissions of bio-based fuels from those of fossil fuels. According to the European Renewable Energy Directive (RED) (European Parliament 2023), the legal framework for the development of clean energy in all sectors of the EU economy, biofuels must result in a 50% GHG saving compared to fossil fuels when produced in older installations, or 65% when produced in new installations.

The savings are calculated using the following equation (European Parliament 2018):

$$\text{Saving} = \left(\frac{E_{F(t)} - E_B}{E_{F(t)}} \right) \qquad (24.1)$$

$E_{F(t)}$ = total emissions from the fossil fuel comparator for transport; E_B=total emissions from the biofuel

The RED gives typical GHG savings for biofuels of, for example, 70% for sugar cane ethanol, 52% for rapeseed biodiesel and, depending on the processing technology, 58–79% for sugar beet ethanol.

According to the RED, greenhouse gas emissions from the production and use of biofuels are calculated by totaling:

+	Emissions from the extraction or cultivation of raw materials
+	Annualized emissions from carbon stock changes caused by land-use change
+	Emissions from processing
+	Emissions from transport and distribution
+	Emissions from the use of the fuel
–	Emission savings from soil carbon accumulation through improved agricultural management
–	Emission savings from CO_2 capture and geological storage
–	Emission savings from CO_2 capture and replacement
	Emissions from the manufacture of machinery and equipment are not taken into account.

It becomes obvious that the assumptions made with regard to land use are critical to the GHG emissions calculated for biofuels. These can even be higher than for fossil fuels if, for example, palm oil is produced on deforested peatland. This calls for the production of low-ILUC biomass, i.e. biomass whose production does not require land-use changes or the use of fertile agricultural land that could also be used for the production of food crops.

Indirect land-use change (ILUC) can occur when energy crops are cultivated on existing agricultural land previously used for the production of food or feed crops. As the demand for food and feed crops remains, their production may be transferred to other areas. If these other areas are not agricultural land but, for example, forests or permanent grassland, this change in land use can potentially lead to CO_2 emissions from carbon-rich soils in these land-use systems or to a loss of biodiversity.

For this reason, under EU rules, an ILUC factor has to be included in the assessment of GHG emissions. Here, all energy crops that use land are assigned an ILUC factor. Feedstock production that does not require agricultural land, such as residual, waste or algae biomass, is exempt from this requirement.

The amount of nitrogen fertilizer applied also has a strong impact on GHG emissions, as nitrogen fertilization is associated with both high direct and indirect GHG emissions. Therefore, dedicated energy crops with high nitrogen fertilization requirements are at a disadvantage compared to crops with high nitrogen-use efficiency.

The energetic use of biomass is at the bottom of the value pyramid and should be at the end of the use cascade (see ▶ Chap. 17). Although dedicated energy crops are currently the main feedstock for liquid biofuels, more second generation biofuels from lignocellulosic biomass or organic waste should be used in the future.

Biogas plants play an important role in integrated bioenergy production. They can already convert organic waste biomass, including slurry, into methane, thereby reducing GHG emissions from slurry treatment.

A sustainability standard and certification system for bioenergy and biofuels has been developed and is operated by the Roundtable on Sustainable Biofuels (now Biomaterials) (RSB) (see ▶ Sect. 35.2 on certification).

Do you want to learn more about the energetic potential of agricultural residues and biogenic waste streams? Take a look at Supplementary Video 24.1, a video from our MOOC "Concepts of Sustainable Bioeconomy" (2021).

Questions

1. What are traditional versus modern bioenergy pathways?
2. What are the main technologies of modern bioenergy production?
3. What are the main factors determining the greenhouse gas mitigation potentials of biofuels?

Answers

1. Traditional use of biomass for energy production includes cooking and heating through combustion, mostly with low efficiency. Modern bioenergy pathways use biomass more efficiently and include heat and power generation, for reasons of efficiency, preferably in combined production and in modern stoves and transport biofuels.
2. Modern bioenergy pathways range from direct combustion for heat and power generation to more advanced processes such as gasification, pyrolysis, fermentation, hydrothermal liquefaction, anaerobic digestion and transesterification, through which energy from biomass can be harnessed to produce electricity, heat and transportation fuels.
3. The so-called GHG mitigation potential is calculated by subtracting the GHG emissions of bio-based fuels from those of fossil fuels. The GHG reduction potential of bioenergy depends on the amount of GHGs emitted during the production of the feedstock, including land use change impacts, and during processing. It is higher for biofuels whose feedstock supply does not require additional land use, such as residual biomass, or is high in demand for nitrogen fertilizer supply.

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Digitalization in Processing

Elia Henrichs, Julia Senge, and Christian Krupitzer



Fig. 25.0 Digitalization in processing. (© Universität Hohenheim, Max Kovalenko) (► https://doi.org/10.1007/000-hv6)

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Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/978-3-032-09098-0_25. The videos can be accessed individually by clicking the DOI link in the accompanying figure caption or by scanning this link with the SN More Media App.

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The rapid advances in artificial intelligence (AI) are opening new possibilities in data processing and analysis and are slowly finding their way into the bioeconomy. The potential of AI in food processing is immense, as it can be used to optimize systems and processes, thus minimizing production-related food losses or optimizing product quality. Similarly, the progressive developments in the Internet of Things (IoT) are leading to the increasing networking of information systems and enabling a comprehensive data exchange. These new technologies, especially those systems that often integrate a wide range of sensors for measuring the environment (e.g., temperature, humidity or acceleration), product-related parameters (e.g., pH value, colour, or gas escape) or process-related parameters (e.g., volume flow, pressure or machine parameters), are paving the way for a more efficient and sustainable future in food processing. This chapter explains state-of-the-art information technology concepts, mainly AI, machine learning (ML), IoT, and digital twins. Digital twins, in particular, are an emerging technology that is gaining traction in the food processing industry. The chapter further elaborates on how to apply these technologies for monitoring food quality and processing, providing a comprehensive understanding of the latest trends in the field.

Learning Objectives

After studying this section, you will…

- …be able to define artificial intelligence and machine learning (see ► Sect. 25.1).
- …be able to describe key elements of the digitalized food supply chain (see ► Sect. 25.2).
- …be able to illustrate the potential of digital twins for process analysis (see ► Sect. 25.3).
- …be able to evaluate the potential of information technology for processing in bioeconomy applications (see ► Sect. 25.4).

25.1 Artificial Intelligence Creates New Opportunities

Artificial intelligence (AI), machine learning (ML), artificial neural networks, and deep learning are terms often used interchangeably, although each represents a specific concept. In the following, they will be defined and distinguished.

> ***Machine learning*** *(ML)* uses algorithms to recognize patterns in potentially very large datasets and extracts those patterns into models to make accurate predictions on new unknown data.

ML uses learning algorithms that implement mathematical or statistical rules to identify patterns in the data. With the increasing available computational power, the role of artificial neural networks has become more important recently, especially as those can analyse very large datasets.

> ***Deep learning*** *(DL)* is a form of ML that refers to artificial neural networks with two or more intermediate layers, called ***deep neural networks***. ***Artificial neural networks*** are structures that mimic the human brain. They consist of several layers (input, intermediate and output layers), each consisting of one or more neurons. The neurons process information by combining input functions, different weightings and activation functions.

Deep learning algorithms require very large datasets and much computational power. However, they can automatically extract the relevant features for learning from the raw data and handle very large datasets. These

algorithms are commonly used for audio or picture recognition.

> ***Artificial intelligence*** *(AI)* is an overarching term for systems that can perform tasks that normally require human intelligence.

The term AI can be defined very broadly and encompasses different approaches and technologies (Russell and Norvig 2021). It might be feasible for AI systems to integrate ML to extract relevant information from data, but it is not a requirement. Conversely, ML might be used just for data analysis and not integrated into an AI system.

25.1.1 Different Approaches to Machine Learning

Essentially, ML is divided into three groups: supervised learning, unsupervised learning and reinforcement learning.

> ***Supervised learning*** aims to describe the relation of features (transformed from data variables) to classes (called classification) or numerical values (called regression). An ML model created using training data can then predict the class/value for previously unknown data.
> ***Unsupervised learning*** divides data into meaningful groups (e.g., clusters), whereby data points in the same groups are more similar than in other groups.
> In ***reinforcement learning***, agents interact with their environment and learn optimal behaviour from feedback.

The following will focus on supervised learning, which is applied in many applications, e.g., regression of values, picture recognition, or classification tasks. The process of ML generally consists of two phases: the offline or training phase and the online or application phase. The training phase focuses on data collection, data pre-processing (e.g., treating missing/wrong data), model selection by comparing different learning algorithms, model configuration, model training, and finally, model evaluation. This phase is often very computationally intensive, and the data quality is crucial, as the "garbage in – garbage out" principle applies: Models can only recognize what was contained in the training data, which can lead to challenges such as class imbalance or bias. For example, product quality control using ML can be challenging if insufficient data for products of insufficient quality is present in the dataset. Solutions to such problems include adding more (measurement) data, over—and undersampling, and using synthetic data (augmentation).

The online or application phase involves model provision, ongoing data management, and maintenance. In contrast to the training phase, this process can also be carried out on less powerful computers, as the pure application of the already trained model to new data is less computationally intensive. However, the application phase requires careful monitoring to ensure that the model responds appropriately to real-time data to make adjustments where necessary and thus maintain or improve performance. Thus, both phases can be iterative if, e.g., the data collected in the application phase is used to retrain the models.

25.1.2 Current Trends in the Field of AI

Generative AI is a special subset of artificial intelligence that aims to generate new content such as images, videos, text, or even music, through a probabilistic approach that closely resembles the original training data. However,

a major problem with generative AI is the reliability of the generated results, as they can often be difficult to interpret or unpredictable.

In general, AI-generated results are often not directly comprehensible, especially if they were generated using deep learning methods. This can be remedied by *explainable artificial intelligence* (XAI), which aims to make the decision-making processes of AI models more understandable and comprehensible. Particularly, this is relevant in critical applications where it is important to understand why a model makes certain decisions or for causality analysis when a model does not produce correct results. However, not every ML method provides explainable models; deep learning technologies, in particular, require an additional component that can generate the explanations post-hoc—the implementation of which can be complex.

Transfer learning is a machine learning technique in which a model already trained for a task is optimized for a new, related task. This enables the use of previously acquired knowledge and accelerates the training for new tasks.

Federated learning is an innovative method in which several models are trained simultaneously in a decentralized manner on different devices without exchanging sensitive information between the devices. The key component lies in aggregating the locally trained models, which ensures data protection and security in distributed environments.

25.2 The Digitalized Food Supply Chain

A prerequisite for using AI in the food supply chain is providing real-time information along the supply chain for food supply, especially from the processing plant to the consumer (Krupitzer and Stein 2024). The use of intelligent packaging enables information about the current condition of the food to be provided. With other technologies, this information can be efficiently evaluated and shared among the stakeholders of the supply chain (Fig. 25.1). Such technologies can be *EdgeML* (Sicking et al. 2019)—i.e., machine learning models and algorithms designed to be deployed and processed directly by the devices, such as sensors or IoT devices, rather than on cloud servers—and blockchain technology for decentralized data storage that records transactions across multiple stakeholders in a way that ensures the data is secure, transparent and tamper-resistant.

> ***Intelligent packaging*** consists of intelligent materials or objects that monitor "the condition of packaged food or the food's environment" through their behaviour (The Commission of the European Communities 2009).

Therefore, indicators and sensors are integrated into the packaging (Müller and Schmid

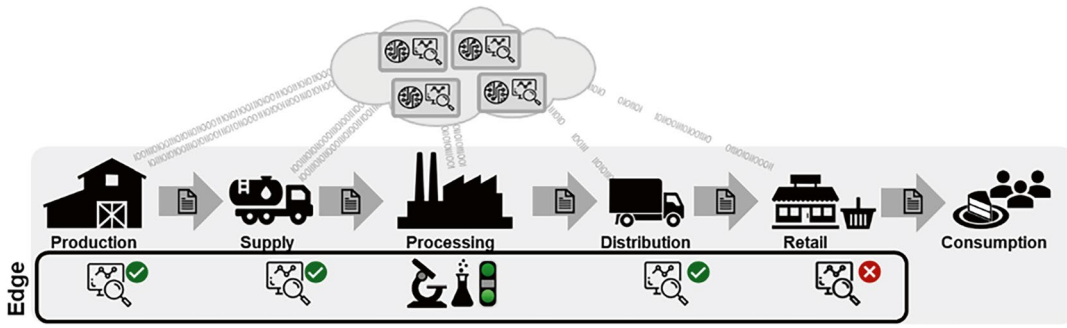


Fig. 25.1 The intelligent, digitalized food supply chain combines smart sensors with EdgeML for efficient data analysis and blockchain technology for data storage

2019). *Indicators* can only directly display the presence or absence of substances or the extent of parameters such as temperature, pH value, or humidity through the binding of an analyte to a specific receptor that triggers a chemical reaction, which is indicated by a colour change (Ghaani et al. 2016).

In contrast, *sensors* quantify the intensity of these parameters, and the *transducer* transfers these values into an electronic signal (Vanderroost et al. 2014; Ghaani et al. 2016). It is, therefore, advisable to use sensors in the packaging of biological products to measure physical and chemical parameters. Like indicators, sensors in intelligent packaging monitor parameters such as temperature, pH value, humidity, pressure on the food or vibrations during transportation (Mondal et al. 2019); however, sensors provide the exact values at a specific point in time—indicators only that a value was outside a defined range. In addition, gas sensors measure the concentration of carbon dioxide (CO_2) or hydrogen sulfide (H_2S) to conclude the current condition of the food (Müller and Schmid 2019). Another widely used type of sensor is biosensors, in which the receptors consist of biological materials such as enzymes, antigens, hormones or nucleic acids. For example, biosensors can react by detecting pathogens in bacteria-contaminated food and turning a barcode into an unreadable state so the food cannot be sold anymore (Ghaani et al. 2016).

The collected data can be sent to information systems with communication technologies such as RFID or NFC (Vanderroost et al. 2014). There, it can not only be analysed to determine the current quality of the food but can also be used to generate further forecasts or to manage the supply chain efficiently. Using EdgeML technology, the data can be processed at the point of origin. This can be useful to reduce the delay by avoiding a transfer to a server or preserving data privacy.

25.3 Digital Twins for Real-Time Analysis of Bio-Based Products

With the development and digitalization towards Industry 4.0, the concept of digital twins has found its way into the industry.

> A ***digital twin*** is the digital representation of an active, unique product (a real device, object, machine, service, or intangible asset) or a unique product-service system consisting of a product and an associated service (Stark and Damerau 2019).

The digital twin enables the integration of real-time data and simulations, allowing continuous monitoring, analysis and optimization throughout the life cycle of the product or service. The bioeconomy, especially the food industry, is particularly interesting for supporting the highly efficient use of available resources. Digital twins can help reduce food losses.

25.3.1 State-of-the-Art of Digital (Bio-Physical) Twins

In a recent publication, Henrichs et al. (2021) investigated the use of digital twins in the food industry. The research results showed that most applications address primary production (55%), i.e., agricultural applications such as plant growth, monitoring the condition of animals, or controlling entire production systems such as greenhouses. Approximately one-third of the studies focus on the processing stage (31%), mainly the monitoring of individual processing machines (e.g., pasteurization or packaging machines) or entire processing systems/processes, e.g.,

for determining the condition of food products during transportation or at retail.

Most applications of digital twins can be categorized as intelligent or data-driven (39%). In addition to monitoring plants and animals in the agricultural sector, these applications focus primarily on determining and adapting process parameters in food processing by using clustering methods and other ML techniques to improve the systems continuously. A comparable proportion of applications are used for simulation based on mechanistic or physics-based models (31%) and primarily concern plant and animal growth in the production phase or the monitoring of food processing. Other digital twins focus on calculating the quality of fruit and vegetables during distribution by measuring the surface temperature, humidity, or other values. The relatively few applications that apply statistical methods (14%) focus primarily on process control during food processing.

As a consequence of our analysis (Henrichs et al. 2021), we postulated the concept of digital bio-physical twins. Those represent a combination of biological and physical aspects of food processing, integrating data-driven models and traditional simulations. Specifically, these twins simulate the transformation of food materials (such as dairy products) by accounting for the processing environment and the materials' inherent biological, chemical and physical properties. The aim is to create a digital counterpart that mirrors the food's behaviour in real time, allowing for optimization and prediction of quality throughout production.

A core concept is that, especially for food processing, biological and physical processes often proceed independently of machinery actions, as in the case of yogurt fermentation, where bacterial activity plays a crucial role. Traditional digital twins focus heavily on machine data, but digital bio-physical twins also factor in microbiological changes, chemical reactions and variations in raw materials, like seasonal differences in milk (Krupitzer et al. 2022).

25.3.2 Potential for Digital Bio-physical Twins

However, a digital bio-physical twin has additional specific requirements compared to digital twins for the production of material goods, as these cannot be based solely on the processing steps due to the variability of the raw materials but must also take into account the chemical, physical, or (micro)biological product/process properties (Fig. 25.2) (Krupitzer et al. 2022). These digital twins provide relevant information (i) for real-time process control and troubleshooting and (ii)

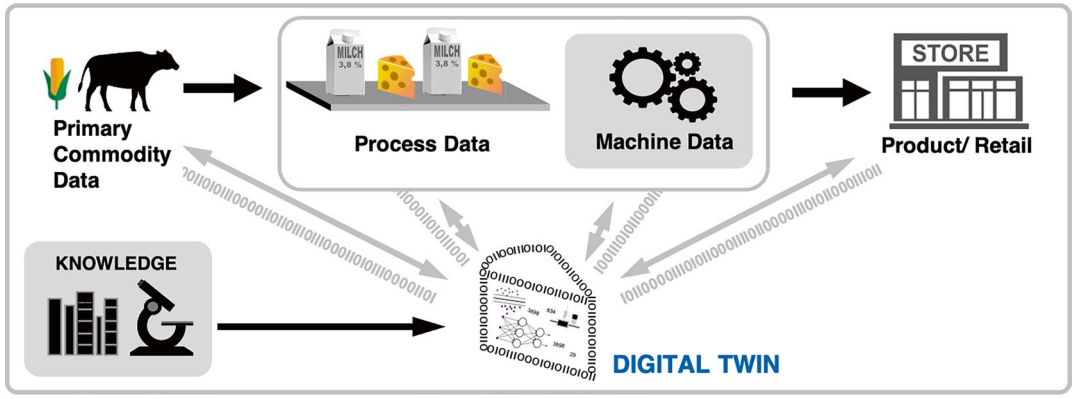


Fig. 25.2 The digital food twin obtains data from the entire food value chain and can monitor and improve food and its production by incorporating theoretical knowledge

for optimizing processes regarding consistency, performance and sustainability. In particular, they can also be used to monitor transportation (keyword: cold chain) and determine the origin (especially compliance with certification standards; see ▶ Sect. 31.2 on certification; more precisely—two aspects that are particularly relevant for food and other bio-based products.

Digital food twins, as one specific example of digital bio-physical twins, can also be used to optimize production planning or form the basis for autonomous systems, but they are also useful in product development. On the one hand, scientific models integrated into a digital food twin can support the creation of new recipes, e.g., the effects of reducing the fat content; on the other hand, they can simplify the scale-up of prototypes (demonstrators) to the production line through simulations based on the data of the demonstrator. Finally, digital food twins can also simulate the effects of packaging on the shelf life of food. A digital food twin could even serve as a replacement for storage tests that are commonly used to predict shelf life (Krupitzer et al. 2022).

25.3.3 Challenges in Implementing Digital Bio-physical Twins for Process Control

One of the biggest challenges in implementing digital twins is the lack of a general method that describes how the information can be transferred from the physical to the virtual object. The specific characteristics of the food sector (e.g., special equipment or hygiene regulations such as HACCP), the complexity of the components (e.g., the variability of the food due to chemical or physical processes), and high-quality standards make the introduction of digital (food) twins difficult. A further challenge is that real-time interaction between the real entities and the virtual twins can only be achieved by further developing sensor, communication, and data processing technologies.

In particular, the complexity and variability of raw materials, their properties, and the limited shelf life of raw food materials and their products limit the application potential. In addition, systems, processes, and knowledge about biological or chemical processes for food production/processing constantly change, which forces the corresponding digital twins to improve constantly.

The lack of good physicochemical data from the processes is another major obstacle to use modelling and simulation tools (Koulouris et al. 2021). In food processing, e.g., many foods with insufficiently described properties that are difficult to calculate or even predict, such as molecular weight, pH value, water activity or thermodynamics, exist. In addition, the kinetics of biological and chemical processes must be understood and made calculable in the form of physical models (Verboven et al. 2020), which can be integrated into the context of *physics-informed machine learning* as the basis for the learning process of artificial neural networks (Purlis 2023). Process models can already be used to estimate the energy and material requirements and the expected process yield during food processing (Koulouris et al. 2021), e.g., determining the energy requirements by simulating the process steps based on previously collected data.

25.4 Industry 4.0 for Bio-based Products

Although, since the 1980s, the industry has been characterized by automation and the use of electronics and IT in manufacturing, it lacks the interconnectedness and real-time data integration necessary for adaptability and efficiency. Those shortcomings resulted in the rise of the concept of Industry 4.0.

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Industry 4.0, often called the fourth industrial revolution, integrates digital technologies into manufacturing processes, combining cyber-physical systems, IoT, and big data analytics with ML to create smart factories (ten Hompel et al. 2016).

The Industry 4.0 revolution is characterized by automation, data exchange, and a fusion of technologies blurring the lines between physical, digital, and biological spheres. Cyber-physical systems especially integrate computation, networking, and physical processes, where embedded computers and networks monitor and control physical processes with feedback loops that allow for dynamic interactions between the physical and digital worlds. Within Industry 4.0 applications, cyber-physical production systems enable real-time data exchange and automated decision-making, leading to highly efficient, flexible and intelligent manufacturing processes.

Industry 4.0 can also revolutionize food processing. AI algorithms enhance quality control by analysing real-time data to detect defects (e.g., using picture recognition) or contaminants in ingredients, ensuring consistent product quality. Digital twins allow virtual simulations of food processing lines, optimizing production parameters without disrupting actual operations. Additionally, IoT devices monitor critical conditions such as temperature and humidity in real-time, ensuring optimal processing environments and enhancing food safety.

In the context of bio-based products, Industry 4.0 offers transformative potential, particularly through the application of digital twins. One specific application is optimizing bioreactors used for fermentation processes. Manufacturers can simulate different conditions, such as temperature, pH, and nutrient concentrations, by creating a digital twin of a bioreactor. This allows for identifying the most efficient production parameters without the need for costly and time-consuming physical trials. The result is improved yield, reduced waste, and enhanced process stability.

Another example of the application of digital twins is the production of bioplastics. Here, digital twins can streamline the polymerization process. By modelling the chemical reactions and flow dynamics involved, manufacturers can fine-tune the process to produce bioplastics with desirable properties such as strength, flexibility, and biodegradability. This enhances product quality and reduces the production's energy consumption and raw material waste.

Furthermore, digital twins can play a pivotal role in supply chain management for bio-based products. Companies can identify bottlenecks, forecast demand, and optimize logistics by simulating the entire supply chain, from raw material sourcing to product distribution. This holistic approach ensures that bio-based products are delivered efficiently and sustainably, meeting market demands while minimizing environmental impact.

Integrating Industry 4.0, particularly through digital twins, into the bioeconomy fosters a more sustainable and efficient industry. These advanced technologies enable precise control over biological processes, reducing resource consumption, lowering emissions, and enhancing product quality. As the bio-based sector grows, leveraging digital twins will be crucial in driving future innovations and meeting global sustainability goals.

Questions

1. What is the difference between AI and ML? How can both be intertwined?
2. How do supervised learning and unsupervised learning differ?
3. You plan to use real-time measurements of products during transportation: Would you use indicators or sensors?
4. Why is a digital twin for bio-based products much more complex than other products?
5. Describe one use case in which a digital food twin is beneficial.

Answers

1. AI focuses on intelligent (software-controlled) systems that can change their behaviour in reaction to system or environment changes. ML is the extraction of knowledge from data. ML mostly supports AI systems by analysing the current or future state of the system/environment.
2. Supervised learning requires a ground truth: Mapping of data (=features) to classes (in the case of classification) or describing a function that relates input and output (in case of regression). If this ground truth is available (and reliable), this approach is preferred as domain knowledge is captured, and the classes reflect causality. Unsupervised learning does not require such a relation between features and a class—it defines the classes solely on the data.
3. Indicators show the presence or absence of a substance, the extent of reactions, or concentrations retrospectively. Sensors measure the physical or chemical properties and constantly determine them quantitatively. Only sensors provide real-time access to the digitized values.
4. Chemical, physical, or biological processes continuously change food products. Hence, the state of the product cannot simply be determined by the process. A digital twin needs to model and simulate those processes. This can enhance monitoring, real-time analysis and predictions, resulting in a bio-physical food twin.
5. In ▶ Sects. 25.3.2 and 25.4, we discussed several applications: product development, scale-up of prototypes (demonstrators) to the production line, process modeling, and supply chain management for bio-based products.

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Process and Product Cost Assessment

Nicolaus Dahmen, Jörg Sauer, and Simon Wodarz



Fig. 26.0 Process and product cost assessment. (© Ricardo Vargas-Carpintero) (▶ https://doi.org/10.1007/000-hv7)

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When a new product or process is developed and introduced, market analyses and cost estimates are required to examine its marketability and the manufacturing or production costs. Before a company takes the decision to construct a production plant and invest in the production and marketing of a certain product, it needs to make sure that the planned process is the most economical and thus the most profitable alternative. In order to make this decision in a sound manner, various tools are used to carry out an economic assessment, weighing up the different costs and revenues against each other. Profitability considerations are also used to develop business plans and assess the state and value of a company. When decisions to invest in chemical conversion plants are taken, a large number of factors have to be taken into account. Hard factors such as profitability and amortisation time are important to outline the investment opportunity. However, they are not sufficient to fully characterize the process and thus correctly assess the investment potential. Soft factors also need to be considered in order to weight up further advantages and disadvantages of an investment. These include a number of criteria relating to the technical process, the location of the production plant and the market situation. Production costs are strongly influenced by the technology applied along with its materials and energy balance. Therefore, process and product cost analysis takes place in early stages and during process engineering. The resulting economic data allow an economic analysis and the creation of a business plan, which help to determine whether a planned project is profitable or not. This chapter provides the fundamental knowledge for this process, together with an example of a cost estimation.

Learning Objectives

After studying this chapter, you will…

- …be able to explain the principles of cost estimation in manufacturing (see ► Sect. 26.1).
- …be able to name the most important cost-determining factors (see ► Sect. 26.1).
- Be able to conduct your own, simple estimates of process investment and manufacturing costs (see ► Sect. 26.2).
- Be able to assess cost assessments given in the literature.

26.1 Cost Assessment

In order to make sound investment decisions, the anticipated manufacturing costs of the product to be commercialised need to be known. Since the exact costs cannot be determined in advance, a cost estimate is performed.

The accuracy of a cost estimate increases as the process development progresses. In this period of time, conceptual and design work is carried out prior to building, expanding or retrofitting a process plant. This includes the determination of all relevant process steps, the type and capacity of equipment, the resources to be used (energy, materials, work, time) and the consideration of all products, desired and undesired. The beginning of the process development is accompanied by a huge uncertainty, up to ±100%, while an accuracy of ±5% is not uncommon close to completion of the project. The *Association for the Advancement of Cost Engineering International* (AACE) proposes a subdivision of cost estimates into five classes (AACE International 2020). These are summarised in Table 26.1 and illustrated graphically in Fig. 26.1. The asymmetric distribution of the uncertainty is particularly apparent.

26.1.1 Investment Costs

Investment costs (*capital expenditure, total capital cost (TCI)*) refer to expenditure that occurs before the plant is commissioned and operated. They consist of *plant costs*, or *ISBL costs* (*inside battery limits*), and off-site costs, or *OSBL costs* (*outside battery limits*). In this context, 'battery limits' means the geographical location on which the plant is constructed. 'Plant costs' refers to expenditure on apparatus, equipment, and other

Table 26.1 Accuracy of cost estimates during process development (AACE International 2020)

Class	Project maturity	Description	Accuracy lower limit	Accuracy upper limit
5	0–2%	Estimate of order of magnitude, within screening and feasibility studies	20–50%	30–100%
4	1–15%	Preliminary estimate, comparison of process alternatives based on conceptual designs	15–30%	20–50%
3	10–40%	Definitive estimate, for acquisition of funding and investors, based on basic engineering	10–20%	10–30%
2	30–75%	Detailed estimate, basis for contracting and project finance control	5–15%	5–20%
1	65–100%	"Check" estimate, after successful negotiation with contracted companies based on detailed engineering	3–10%	3–15%

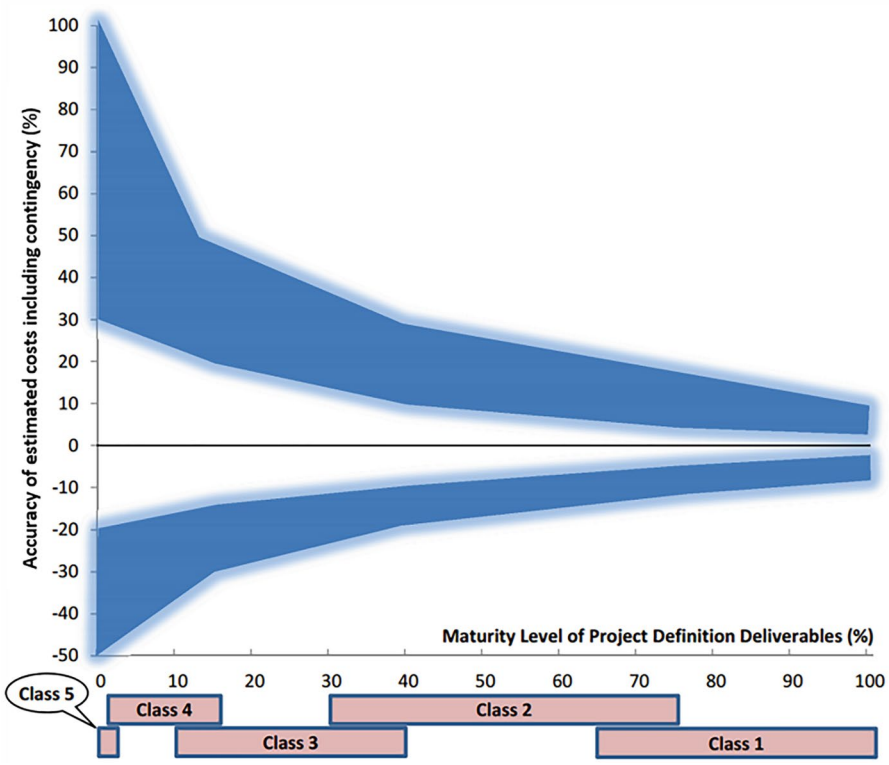


Fig. 26.1 Schematic diagram showing the asymmetrical limits of cost estimate accuracy above and below baseline at different stages of process development. (AACE International 2020)

objects and activities directly required for the planning, construction and operation of a plant, including:

- Main pieces of equipment: reactors, columns, heat exchangers, pumps, etc.
- Pipelines and fittings: Tubes, valves, insulation, paint, etc.
- Instrumentation and control: Temperature, pressure and level sensors, flow meters, process visualisation software, etc.
- Electrical engineering: power supply, wiring, transducers, switches, etc.
- Construction work: Scaffolding, fundament, buildings, etc.
- Plant assembly: Staff and sub-contracting
- Miscellaneous: Fire protection, interfaces (connection to power and media supply)
- Planning and execution: Staff and subcontracting
- Quality assurance
- Contingencies

'Off-site costs' refers to all costs associated with the plant, but not located inside the battery limits, most commonly items such as utilities or ancillaries.

Inside Battery Limits (ISBL) Costs

The main pieces of equipment account for a major share of the ISBL costs. For this reason, these are a good starting point for a first, rough estimate of the investment costs, even though, at the end of the day, they do not provide the largest contribution to ISBL costs.

To obtain a first estimate of the key apparatus costs, simple methods such as the capacitance method are applicable. They can be carried out without specific technological knowledge, purely on the basis of the desired capacity of the new apparatus (or even whole plants) relative to the capacity of comparable, already existing apparatus (or plant).

$$C_2 = C_1 \left(\frac{S_2}{S_1} \right)^n \tag{26.1}$$

C_2 denotes the cost of the new apparatus (or plant) with desired capacity S_2. C_1 denotes the already known cost of an existing reference apparatus with a given capacity S_1. Capacities may be given in mass and volume flows, electrical powers, volumes of reactors and other vessels or the like. The degression or scale-up exponent n indicates how strong the non-linear relationship between capacity and cost is. Where $0 \leq n \leq 1$, a larger apparatus (plant) is, in relation, less expensive than a small device. Long-term experience has shown n to be 0.7 for petrochemical plants, between 0.4 and 0.5 for pharmaceutical and specialty chemicals, and between 0.8 and 0.9 for plants with a high consumption of mechanical work by, for example, compressors.

Apparatus costs, as purchased from the equipment suppliers, are called *free-on-board* (*FOB*). They are generally estimated via the capacity method (Eq. 26.1). Reference size and price are usually provided by the supplier. The degression coefficients for the main apparatuses can vary significantly (Seifert et al. 2012). ◘ Table 26.2 shows data, as typically found in the literature, compiled from (Silla 2003), including the capacity of the reference device (always check the units given!), the FOB purchase costs, the correlation range for which the capacity rule is valid, and the degression exponent.

However, in addition to the purchasing costs of an apparatus, further cost contributions are generated by its installation and integration into the plant. To estimate the total ISBL costs of the planned plant, a *structural method* such as the Lang method is used to determine these costs of connecting pipes, fittings, measuring and control devices, assembly and the like. This method, which was developed by Lang in 1940 (Hirschberg 1999), can only be applied once the required main apparatuses have been determined and dimensioned and their prices are known. Instead of listing the individual prices of all other components (i.e. for each valve, tube, etc.) their costs are related to the main pieces of equipment based on empirical values, for example the cost of pipes lies between 30% and 100% of the main apparatus costs. These empirical values are included in the calculation of the ISBL costs in the form of so-called Lang factors. These factors, which may be different for different types of plants, are added up and then multiplied by the sum of the costs of the

Table 26.2 Example of literature data for estimation of main equipment costs, FOB (Silla 2003)

Equipment	Capacity	Capacity units	FOB cost / 303 US$, (Jan 1990)	Correlation range	Degression exponent
Agitators					
Propeller Impeller	3.0 20.0	hp hp	2.8 12.0	1.0–7.0 3.0–100	0.5 0.3
Air cooler	1.0	ft^2	0.137	–	0.8
Blower, centrifugal	4000	ft3/min	60	$800–1.8{\cdot}10^4$	0.6
Compressor, centrifugal	600	hp	190	$200–1.8{\cdot}10^4$	0.32
Electric motors					
Open drip proof Explosion proof	60 100	kW kW	3.0 9.5	$0.2–5{\cdot}10^3$ $0.3–8{\cdot}10^3$	1.1 1.1
Evaporator Vertical tube	1000	ft^2	180	$100–8.10^3$	0.53
Heat exchanger Shell and tube	1000	ft^2	14	$100–5.10^3$	0.65
Process furnace	20,000	kW	750	$3{\cdot}10^3–1.6{\cdot}10^5$	0.85
Pump, centrifugal					
High range Low range	20 0.29	hp hp	9.0 2.3	2.68–335 0.1–2	0.42 0.29
Reactors, CSTR					
Jacketed Glass-lined	600 400	gal gal	17 33	$30–6{\cdot}10^3$ $30–4.10^3$	0.57 0.54
Rotary vacuum filter	30	ft^2	60	4–600	0.67
Tanks, cone roof					
Low range High range	12.105 12.106	gal gal	170 170	2.10^5—$1.2{\cdot}10^6$ $1.2{\cdot}10^6–1.1{\cdot}10^7$	0.32 0.32

main apparatus to give an estimate of total ISBL costs (Eq. 26.2).

$$\text{ISBL} = LF \cdot \sum_{k=1}^{N} \text{FOB}_k \qquad (26.2)$$

The sum of the Lang factors *(LF)* usually ranges between 2.7 and 6.0. A typical value for chemical plants is, for example, 4.57. A list of the individual factors can be found in Table 26.3. In most cases, additional cost factors need to be taken into account. The tabulated prices often have to be adapted to the following factors:

- Specific technical requirements: corrosion resistance, high pressure and temperature, material compatibility. These need to be considered by separate material factors for each piece of equipment.
- Local factors: local infrastructure, availability and costs of trained staff, transportation costs, transport options.

Table 26.3 Lang factors for the calculation of ISBL costs

Cost type	Structural unit	Factor
Direct ISBL costs	Main apparatus (FOB)	1.00
	Tubing and fittings	0.40–1.00
	Instrumentation and control	0.20–1.20
	Electronics	0.20–0.50
	Construction (buildings)	0.30–1.00
	Plant assembly, installation	0.10–0.25
	Miscellaneous (insulation etc.)	0.10–0.25
Indirect costs	Engineering	0.35–0.50
	Contingencies	0.15–0.30
	LF sum factor	2.70–6.00

– International factors: exchange rates, import fees.
– Annual factors: Inflation, leading to price development for apparatuses and other equipment. Can be considered by a price index, e.g. according to Kölbel/Schulze, available from the VCI (Verband der Chemischen Industrie) at ▶ www.chemietechnik.de

Outside Battery Limits (OSBL) Costs

The off-site costs of a chemical plant depend on the infrastructure available at the location of the planned plant. The OSBL stem from the infrastructure required to provide auxiliary materials (e.g. gases like N_2, O_2, H_2) and energy (in the form of electricity, steam or fuels) as well as for storage, waste disposal, and overall on-site logistics. In general, make-or-buy decisions have to be made, meaning that it is necessary to consider whether it is more cost-efficient to install the infrastructure on-site (within the battery limits) or to buy-in a service via an *over-the-fence contract* with external partners (Sinnot et al.2009).

▶ Example: Purchasing Costs of a Furnace

A pilot plant is to be constructed for the production of a bioenergy carrier by torrefaction of wood pellets. This would usually be fired by hot combustion gases, but the pilot plant is too small for such a design. Instead, the reactor is to be constructed as an electrically heated furnace with a maximum capacity of 5 MW. We need to know the purchasing cost in euros of a furnace with an electrical performance of 40,000 kW to be installed in Germany in 2016. The FOB reference data of a process furnace with a capacity of 20,000 kW, valid from January 1990, can be taken from Table 26.2. The purchase price is given as 750,000 US dollars, and the regression coefficient is 0.85. First, the capacity method is applied using Eq. 26.3 to obtain the price for an oven of the desired capacity:

$$C_{\mathrm{USA},\$,1990} = 750{,}000\,\$\left(\frac{5{,}000\,\mathrm{kW}}{20{,}000\,\mathrm{kW}}\right)^{0.85} = 230{,}840\,\mathrm{US\$} \tag{26.3}$$

Now the price has to be adjusted to the year 2016 by Eq. 26.4. It is assumed that the price of the furnace is similar to that of crude steel (since it is mostly made of steel). Thus, the price increase is mainly given by the steel price development factor. Using European steel prices (IndexMundi) for comparison would also be permissible, since it can be assumed that the prices of globally traded steel have developed in nearly the same way around the world:

$$C_{\mathrm{USA},\$,2016} = C_{\mathrm{USA},\$,1990}\left(\frac{C_{\mathrm{Steel},2016}}{C_{\mathrm{Steel},1990}}\right) = 230{,}840\,\$\left(\frac{54.85\frac{€}{t}}{14.05\frac{€}{t}}\right) = 901{,}180\,\mathrm{US\$} \tag{26.4}$$

Then Eq. 26.5 is used to factor in the location change in the installation of the furnace with a location factor (taken from Sinnot et al. 2009):

$$C_{\mathrm{GER},\$,2016} = C_{\mathrm{USA},\$,2016}\left(\frac{C_{\mathrm{GER}}}{C_{\mathrm{USA}}}\right) = 5.277.607{,}23\,\$\left(\frac{1.11}{1.00}\right) = 1{,}000{,}310\,\mathrm{US\$} \tag{26.5}$$

Finally, using Eq. 26.6, the exchange rate is taken into account to give the purchase costs in Euro for the furnace with 5000 kW purchased in 2016 and installed in Germany:

$$C_{\mathrm{GER},€,2016} = C_{\mathrm{GER},\$,2016} \cdot \text{Exchange rate}$$
$$= 5{,}858{,}144.02\,\$ \cdot 0.90\,\frac{€}{\$} = 900{,}280\,€ \quad (26.6)$$

This results in a purchase price for the electrically heated torrefaction chamber of around 900,000 EUR. The calculation was based on the reference capacity and price taken from literature, and updated by the steel price development (as dominant cost factor) for the actual year of purchase, the change in location of the plant construction, and the US$/EUR exchange rate. ◀

26.1.2 Manufacturing Costs

The manufacturing costs of a product can be divided into variable and fixed costs. For their calculation, it is important that the investment costs and the most important process parameters are already fixed or estimated reasonably accurately. *Variable costs of production* are all costs that occur during the operation of the plant and are dependent on its utilisation. Variable production costs comprise:

- Material costs: Feedstocks, input and auxiliary materials (obtained from the mass balance of the process),
- Energy costs: Steam, fuels (gas, heating oil), electrical power, cooling water, etc. (obtained from the energy balance of the process),
- Waste management: Waste water disposal, off-gas treatment, solid residues, etc.
- Other costs: Analytics, packaging, shipping, etc.

The *fixed costs of production* are all costs incurred during the operation of the plant which are not dependent on the degree of utilisation of the plant. Fixed costs are, for example:

- Capital-related costs: depreciation of investment costs (fixed capital cost),
- Staff costs: wages, salaries, shift premiums, insurances, company bonuses,
- General costs: transport, security, social services, plant management,
- Repairs and maintenance,
- Taxes and insurance.

The capital fixed costs are calculated from the total investment costs, the depreciation time and the production capacity:

$$\text{Capital fix costs} = \frac{\text{ISBL} + \text{OSBL}}{\text{Depreciation time} \times \text{Product capacity}} \quad (26.7)$$

The capital fix costs usually account for the largest proportion of the manufacturing costs. Therefore, they are the most relevant factor in the economic assessment of a production process. Additional costs to be considered for the production and sale of chemical products stem from marketing and selling activities (5–25% of revenues), research (2–5% of revenues, in larger companies), and for generalia such as financial, legal and patent departments (3–5% of revenues) (Baerns 2023). A number of key performance indicators (KPI) are used to calculate the economic performance and profitability of an investment. The earnings (profit) are calculated from the revenues minus all costs within a certain time period. The profit depends on how much product can be sold to the market at the anticipated price. Thus, the earnings are directly related to the workload of a plant and primarily determined by the fixed (also incurred when the plant is not in operation) and variable costs of production.

26.2 Cost Estimation Example

Synthesis gas, a mixture of hydrogen and carbon monoxide, can be produced from lignocellulosic biomass, for example, in the Bioliq® process at KIT (Dahmen et al. 2016). For this process, biomass is pretreated decentrally (close to the place of production) by fast pyrolysis to produce an energy-dense intermediate, which is collected from a number of these decentral plants to be further processed in industrial-scale facilities. There, it is gasified to produce syngas, which, after cleaning, can in turn be used to produce various types of fuels and chemical products. Figure 26.2 shows a block flow diagram of the downstream production of gasoline in a hypothetical process. The mass and energy balance of a process is usually available from process simu-

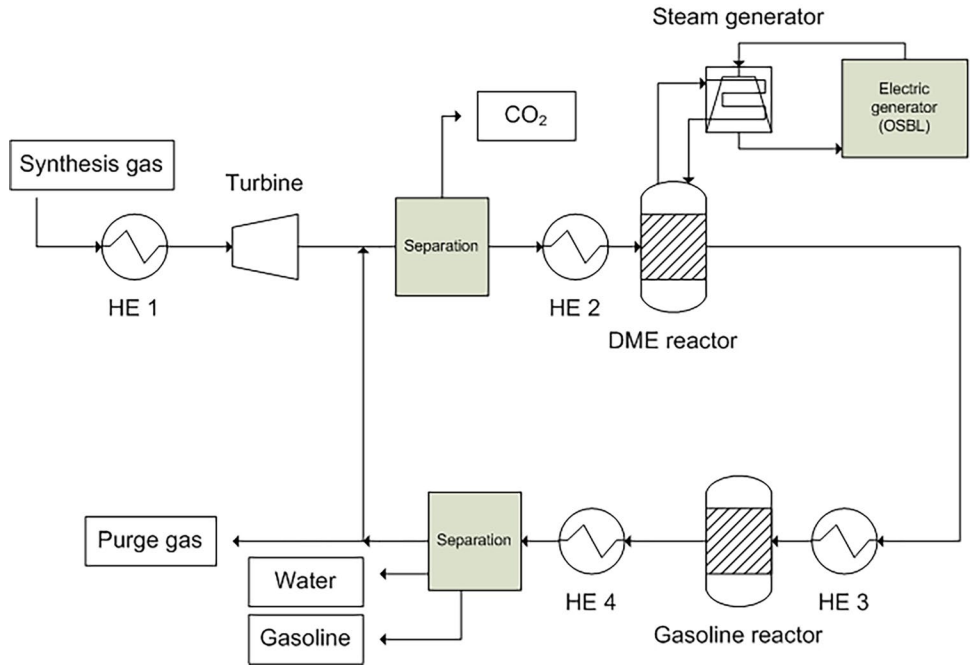


Fig. 26.2 Block flow diagram of gasoline production from synthesis gas

lation using software tools like ASPEN Plus or CHEMCAD. All the main pieces of equipment form blocks of unit operations (cooling, heating, pumping, filtration, distillation, reaction, etc.) characterised by specific operating conditions combined with input and output streams of defined composition and conditions. Here, to reduce the complexity, we only consider the synthesis of the raw product for cost estimation. After an initial heat exchange (HE1), the high-pressure syngas (in the Bioliq® process, a high-pressure gasifier is utilized) passes through a turbine producing electricity. Then, the CO_2 contained in the syngas (formed by partial oxidation in the previous gasification process) is separated at ambient temperature. In heat exchanger HE2, the temperature is adjusted for the first synthesis reactor. Here, the syngas is converted at 200 °C and 35 MPa into dimethylether (DME) in an exothermic reaction using a mixed catalyst that facilitates methanol synthesis, its dehydration, and the water-gas-shift reaction all at the same time (sum reaction equation: $3\ CO + 3\ H_2 \rightleftarrows CH_3OCH_3 + CO_2$). After reaction, a heat exchanger (HE3) is utilised to adjust the temperature to the optimum for gasoline synthesis over a zeolite catalyst at around 340 °C (sum reaction equation: $CH_3OCH_3 \rightleftarrows -(CH_2)- + H_2O$, where $-(CH_2)-$ stands for a formal hydrocarbon fuel unit in the resulting fuel mixture). The gas is then cooled down by heat exchanger HE4 prior to separation of raw gasoline, water formed during the reaction and non-reacted gas. Half of the remaining gas is recycled to the DME reactor.

A process simulation is carried out with some necessary assumptions to give a materials and energy balance: the syngas composition is fixed (30 vol.% of H_2 and CO each, 20 vol.% CO_2, 15 vol.% N_2 and 5 vol.% H_2O), the conversion of syngas to DME is 0.85 and that of DME to gasoline is 1.0. Side products are not considered. 20,000 kg of gasoline are produced per hour. Process simulation is extremely helpful when heat shifts are necessary: the heat of both exothermic reactions is to be used to pre-heat colder input streams and to produce steam for use in other parts of the plant. Therefore, efficiencies have to be considered: that of heat exchange is assumed to be 0.8 and that of steam generation 0.5. From the simulation, the desired capacities of

the equipment can be derived for materials (kmol/s), power (MW) and heat exchangers (m^2) as given in ◘ Table 26.4.

In this example, the specific manufacturing costs are to be estimated for the year 2014 in EUR. It is assumed that the production plant is operated for 7000 hours per year, and a depreciation time of 10 years has been accepted. The specific production costs (in EUR/kg) are calculated below according to the following scheme (◘ Fig. 26.3).

In ◘ Table 26.4, the main pieces of equipment are compiled together with the reference costs, the reference and the desired capacity

◘ **Table 26.4** Calculation of TCI and capital fixed costs using the example of synthetic raw gasoline production from syngas

	Reference capacity	Capacity unit	Desired capacity	Reference costs/EUR[a]	Degression coefficient	FOB costs/ US$
1. Total investment cost calculation						
1.1 ISBL calculation						
1.1.1 FOB calculation						
HE1	609	m^2	609	224,536	0.6	224,536
Turbine	5.3	MWe	5.3	1,193,186	0.6	1,193,186
HE2	571	m^2	571	212,062	0.6	212,062
DME reactor	1	kmol/s	2.16	4,365,974	0.65	7,195,800
HE3	386	m^2	386	177,134	0.6	177,134
Gasoline reactor	1	kmol/s	1.36	4,365,974	0.65	5,340,334
Steam generator	1	MW	24.2	216,943	0.6	1,466,279
HE4	384	m^2	384	177,134	0.6	177,134
Separation unit						18,750,000
				FOB total/EUR		34,736,464
1.1.2 Application of Lang factors						
Piping and fitting	0.46				15,978,773	15,978,773
Instrumentation and control	0.24				8,336,751	8,336,751
Electronics	0.2				6,947,293	6,947,293
Construction	0.7				24,315,525	24,315,525
Plant assembly	0.28				9,726,210	9,726,210
Engineering	0.4				13,894,585	13,894,585
Contingencies	0.3				10,420,939	10,420,939
				ISBL total/EUR		124,356,540

(continued)

26

Table 26.4 (continued)

	Reference capacity	Capacity unit	Desired capacity	Reference costs/EUR[a]	Degression coefficient	FOB costs/ US$
1.2 OSBL calculation						
Power generators						17,500,000
				OSBL total/EUR		17,500,000
1.3 TCI calculation						
				Total investment cost/EUR		141,856,540
2. Fixed capital cost calculation						
Gasoline production capacity	20,000	Kg				
Annual operation time	7000	h				
				Fixed capital cost/EUR a^{-1} kg^{-1}		0.101

[a]Derived from Table 26.5

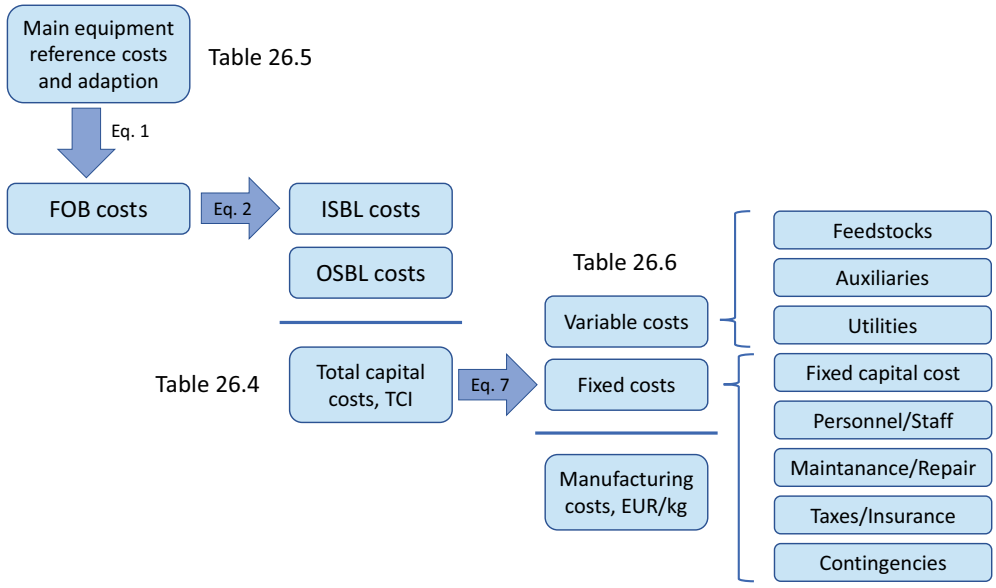


Fig. 26.3 Manufacturing cost calculation scheme

and degression coefficients. These allow cost determination of the equipment in the desired size according to the capacity method. For CO_2 and product separation, additional costs of 18,750,000 EUR are assumed without further details.

Because reference costs can usually only be found for past years and are typically given in US$, conversion is required to obtain the actual costs (2014, with price development factor 1.35) in the appropriate currency (EUR, at 1€ = 1.25 US$). Since the date of the reference and currency are not necessarily the same for all pieces of equipment, it is recommended that this procedure is applied for each item. Material factors are also taken into account by using stainless steel instead of carbon steel for most pieces of equipment. The conversion of reference costs given in the literature to reference costs that take price development, exchange rate and material factors into account is given in Table 26.5.

From these data, FOB costs are calculated according to Eq. 26.1. Then, Lang factors are applied to the FOB total, to give the ISBL costs. By adding OSBL costs, the total capital investment costs, TCI, are obtained. Power generation is assumed to have an efficiency of 100%; losses have already been taken into account in the low steam generation efficiency.

Manufacturing costs are calculated from variable and fixed cost contributions in Table 26.6. Syngas is treated as a buy-in product, which is typical for large plant complexes, where the individual plants are considered as separate business units. Since the heat produced in the highly exothermic reactions is made use of, excess energy can be exported. As such, no energy costs are incurred; in contrast, revenues are gained from power export. Given the highly variable cost contributions of feedstock, those for auxiliaries can be neglected here.

To calculate the fixed costs, the fixed capital costs (as given in Table 26.4), and costs for personnel, repairs and maintenance, as well as taxes and insurances, are considered. The last two are usually expressed as a percentage of the total investment costs. Typical values for chemical plants are given in Table 26.6. Such plants usually require personnel for 5 shifts as well

Table 26.5 Reference cost adaption for FOB calculation

	Reference costs US$, 2002	Reference costs EUR 2002 (factor 1/1.25)	Reference costs EUR 2014 (factor 1.35)	Material factor	Reference costs EUR, 2014 Stainless Steel[a]
HE1	90,000	72,000	97,624	2.3	224,536
Turbine	550,000	440,000	596,593	2	1,193,186
HE2	85,000	68,000	92,201	2.3	212,062
DME reactor	1,750,000	1,400,000	1,898,250	2.3	4,365,974
HE3	71,000	56,800	77,015	2.3	177,134
Gasoline reactor	1,750,000	1,400,000	1,898,250	2.3	4,365,974
Steam generator	200,000	160,000	216,943	1	216,943
HE4	71,000	56,800	77,015	2.3	177,134

[a]Input data for Table 26.4

Table 26.6 Determination of manufacturing costs

Manufacturing costs	EUR/kg	EUR/a	
Variable costs			
Syngas	0.214 EUR/kg	1.905	266,704,873
Energy (utilities)			
Revenues from power generation	0.05 EUR/kWh	- 0.060	- 8,456,432
Auxiliaries (catalyst/water)		Negligible	Negligible
	Total variable costs	1.845	258,248,441
Fixed costs			
Fixed capital costs		0.101	14,185,654
Personnel		0.004	590,000
Repairs/maintenance	5% of total capital costs	0.005	709,283
Taxes/insurance	1.5% of total capital costs	0.002	212,785
	Total fixed costs	0.112	15,697,722
	Total manufacturing costs	1.957	273,946,162

as a day shift. A typical team would be composed of a plant engineer, some administrative staff, shift engineers and operators, and technicians for the repair of mechanical and electrical devices. Here, the equivalent of 10 full-time staff is assumed.

26.3 Economic Considerations

The results of the cost calculation example given above reveal that, in total, 273,946,162 EUR per year or 1.957 per kilogram need to be earned through the sale of the product to cover the investment costs before any profit can be made from it. There are a number of economic indicators that can give information on the financial state of a company, a process or project operation These indicators also allow comparison of different process alternatives and sensitivity analyses, e.g. by changing feedstock, energy, selling prices or other variables with time. Here are some of the most important measures for accounting and finance with practical, somewhat simplified definitions.

Revenue is the amount of money that a company receives in a certain period of time. In the cost calculation example above, it is money earned by selling the gasoline product, calculated by multiplying the price (which is usually higher than the production costs!) by the amount of product sold in that period of time.

In this context, **costs** refers to the amount of money or monetary valuation expended in order to produce, market, sell and deliver the product.

Profit is obtained when the amount of revenue gained from a business activity exceeds the costs, thus:

Profit = Revenues – Costs.

It is worth mentioning that the profit is strongly dependent on the amount of marketed product or its selling price. Therefore, there is always pressure on process optimisation to reduce fixed and variable cost contributions.

Earnings before interest and taxes (EBIT) are a measure of the company's profit that includes all expenses except

interest and income tax expenses. This indicator is usually applied to whole companies for the purpose of benchmarking and comparison, but can also be applied to individual parts of the business or processes operated.

In contrast to EBIT, the ***Earnings before interests, taxes, depreciation and amortisation (EBITDA)***, do not include depreciation and amortisation in the calculation. It is closely related to cash flow as one of the most important key performance indicators.

Cash flow is the net amount of cash moving into and out of the business in a specified period of time. It is used to assess the quality of a company's income, that is, how liquid it is. It is calculated as the difference between revenues and expenses without considering interest, taxes and amortization.

Profitability is a measure of the efficiency of the employed capital investment by relating investment costs to achieved profit. It can be used to compare different business models and process alternatives.

The ***return on capital employed*** (ROCE) relates revenues without interest and taxes (EBIT) to the capital employed. The reciprocal value is the time required to recoup the investments made (payout time).

The ***Net Present Value*** *(NPV)* is the difference between the present value of cash inflows and present value of cash outflows at a certain time. NPV is used to determine the profitability of a projected investment and includes the consideration of taxes. It is calculated by the following equation.

$$C(n) = \sum_{t=0}^{n} \frac{c_t}{(1+i)^t} \qquad (26.8)$$

where $C(n)$ is the NPV in year n, c_t is the cash flow, i is tax and t the number of years.

Figure 26.4a shows the cash flow for a project to produce synthetic gasoline on the basis of the example given in ▶ Sect. 26.2. In this example, the investment is made to plan, design and construct the production plant within three years. In this period of time, the investment costs expended result in negative cash flows. After this period and following commissioning, the plant produces a fixed amount of product at the same costs and profits (40,000,000 EUR per year). Figure 26.4b shows the NPV curve after interest has been paid. It can be seen that the payout time is achieved after 9 years. This and several other factors are most relevant for decision making in companies and, in particular, profitability of projected investments.

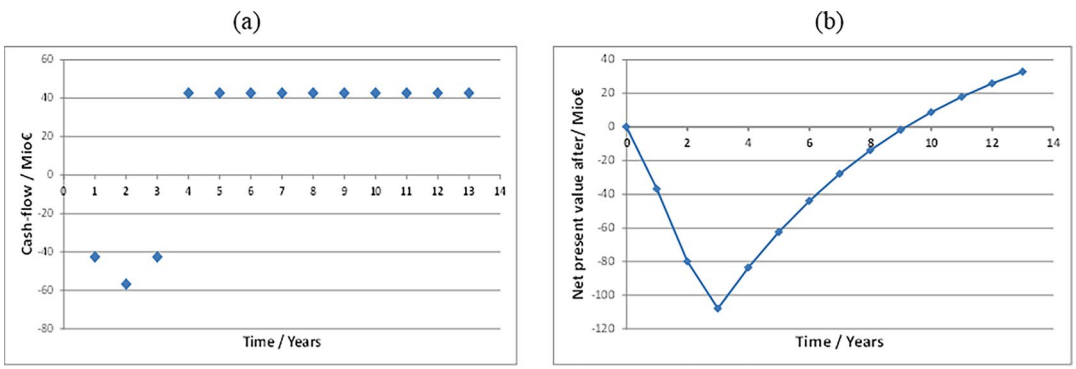


Fig. 26.4 Cash flow and net present value curves for a three-year investment period

Questions

1. Which simple method can be used for a first, rough cost estimate of a plant, when the technology is already state-of-the-art?
2. What are the main cost contributions in manufacturing costs?
3. Why are capital fixed costs so relevant to manufacturing costs?
4. What are the differences between ISBL and OSBL and between variable and fixed costs?
5. What are the most relevant economic key indicators? How do they differ from each other?

Answers

1. The main pieces of equipment account for a major share of the ISBL costs. For this reason, these are a good starting point for a first, rough estimate of the investment costs. To obtain a first estimate of the key apparatus costs, simple methods such as the capacitance method are applicable. They can be carried out without specific technological knowledge, purely based on the desired capacity of the new apparatus.
2. The capital fix costs usually account for the largest proportion of the manufacturing costs.
3. The capital fix costs usually account for the largest proportion of the manufacturing costs. Therefore, they are the most relevant factor in the economic assessment of a production process.
4. Investment costs (capital expenditure, total capital cost (TCI)) refer to expenditure that occurs before the plant is commissioned and operated. They consist of plant costs, or ISBL costs (inside battery limits), and off-site costs, or OSBL costs (outside battery limits). The off-site costs of a chemical plant depend on the infrastructure available at the location of the planned plant. The OSBL stems from the infrastructure required to provide auxiliary materials (e.g. N_2, O_2, H_2) and energy (in the form of electricity, steam or fuels) for the disposal of waste materials as well as for storage and overall on-site logistics. Variable costs of production are all costs that occur during the operation of the plant and are dependent on its utilization.
   The fixed costs of production are all costs incurred during the operation of the plant, which are not dependent on the degree of utilization of the plant
5. Revenue, Costs, Profit, Earnings before interest and taxes (EBIT), Definition Earnings before interests, taxes, depreciation and amortisation (EBITDA, Definition Cash flow, Definition Profitability, Definition Return on capital employed (ROCE), Definition Net Present Value (NPV).

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Markets for Bio-based Products & Economics for a Sustainable Bioeconomy

In the first of this part of the textbook, we take a closer look at the functioning and status of global markets for bio-based products—using the examples of biofuels, biochemicals and bioplastics—and how they interact with agricultural and food markets. We also look at policy instruments—such as carbon taxes and blending mandates—for steering market developments. The second focuses on how scarce resources can be best allocated in a bioeconomy. The optimal allocation of limited productive resources is crucial to achieving sustainability across economic, social and environmental dimensions. A multifaceted economic framework, essential for advancing a sustainable bioeconomy, is described through the introduction of perspectives from welfare economics, environmental economics, and climate and energy economics, the latter of which explores the potential of the bioeconomy to mitigate climate change.

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Markets of Bio-based Resources and Products

Kirsten Boysen-Urban, Ole Boysen, and Carolina Schiesari



Fig. 27.0 Markets of bio-based resources and products. (© Hamburg, Port) (▶ https://doi.org/10.1007/000-hv8)

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This chapter takes a closer look at the global market for bio-based products and resources and its interactions with agricultural and food markets. In particular, it describes the effect of increasing demand for bio-based products on market prices and thus the quantity of agricultural resources demanded and supplied. Furthermore, we discuss factors that may drive or limit the demand and supply of bio-based products. We analyse the market for bio-based resources and products, considering products that are already established in the market, such as biofuels, as well as products that could acquire a substantial market acceptance in the future, such as biochemicals and bioplastics. In addition, we briefly introduce selected policy instruments applied to support bio-based products. The chapter provides a simple example of a perfectly competitive market for bio-based products to introduce the market model. It starts by presenting the supply and demand curves and discussing the differences between price changes and those of other determinants of supply and demand with respect to their effects on the respective curve. It then explains how the supply and demand curves jointly determine the equilibrium price and quantity on the market and how the market price regulates surpluses and shortages under the assumption of an autarkic country. We apply this market model to demonstrate the effect of one particular policy for promoting the production of bio-based products on the equilibrium market price and quantity.

Learning Objectives

After studying this section, you will…

- …be able to trace and explain the functioning of resource and product markets and the price mechanism (see ► Sect. 27.3).
- …be able to analyse the effects of supply and demand shocks on the market for bio-based products and understand interlinkages with food and feed markets (see ► Sect. 27.4).
- …be able to explain policy effects and how they can be used to influence the markets for bio-based products (see ► Sect. 27.5).

27.1 Introduction

Concerns about the exhaustion of natural resources and climate change have raised interest in the production of bio-based products. This has been driven in particular by the depletion of limited global natural resources such as oil reserves (see ► Chaps. 1 and 2), the dependency on oil-producing countries and the increasing number of agreements on environmental protection and climate change mitigation. As a consequence, governments are increasingly endeavouring to support the production of bio-based products through policies. The associated political objectives include sustainable production and achievement of sustainable development goals, reduction of environmental pollution, mitigation of climate change effects and increased self-sufficiency in energy production thus lowering dependence on oil-producing countries, such as Organization of the Petroleum Exporting Countries (OPEC) members and other politically unstable regions. However, the market for bio-based resources and products also faces several limiting factors. The production costs of bio-based products are often much higher than those of "unsustainable" products already established on the market. As a result, bio-based products are often not competitive at current market prices. Their future competitiveness requires continued research and development, which—due to market failures—may not occur without some temporary government interventions, such as subsidies, public procurement, blending mandates and the establishment of labelling or certification programs that distinguish these products from traditional ones, attesting their higher value and thus justifying to charge viable prices.

Figure 27.1 lists the major driving and limiting factors in the demand and supply of

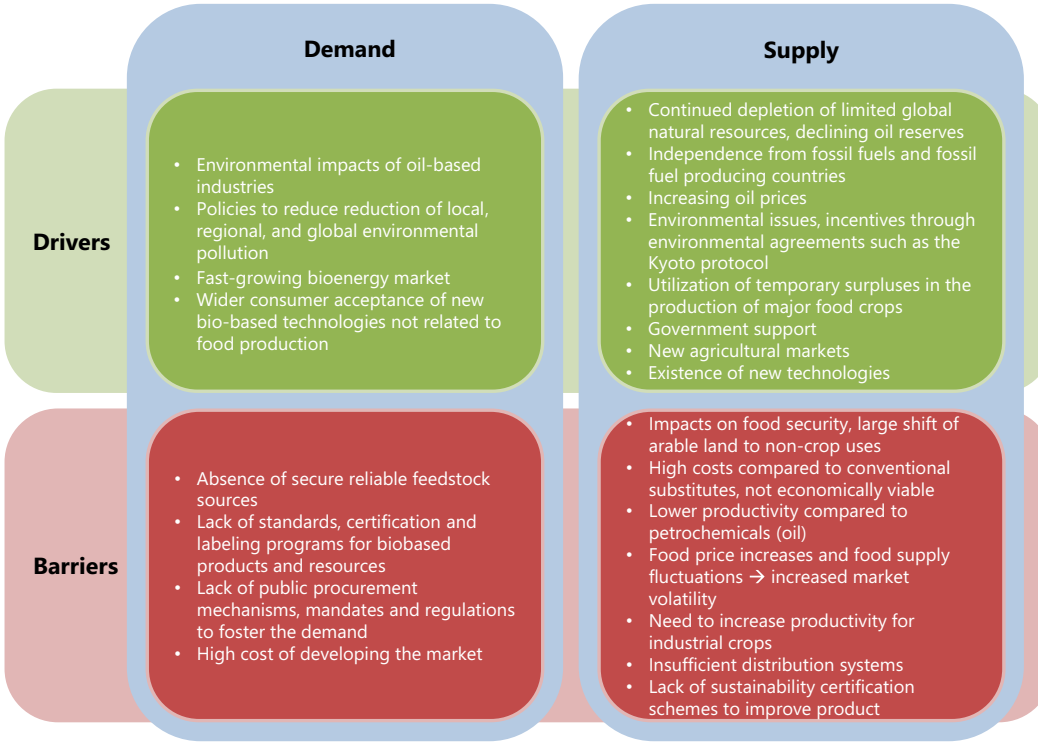


Fig. 27.1 Major driving and limiting forces in demand and supply of bio-based resources and products. (Source: Own elaboration)

bio-based products and resources. The continuous growth in the global population, together with changes in diets through improved living standards, has led to sharp increases in the demand for food and feed products. On the other hand, climate change and finite fossil fuel resources are driving additional demand for bio-based products. Since bio-based products are often at least partly based on primary agricultural commodities, this can create a conflict with food security objectives through the competition for limited resources, such as land, water and other inputs to agricultural production. For example, additional demand for agricultural products as feedstock for biofuels production has been identified as one of the factors that triggered the food price spikes in 2007/2008 and 2011.

Global biofuel production has increased significantly over the past decade, reaching record levels before Russia's invasion of Ukraine in 2022. For example, the United States, the leading producer of renewable ethanol, used more than a third of its total corn production for ethanol. Recently, the rise in food prices as a result of the war in Ukraine has increased the risk of food insecurity, particularly in net-importing developing countries that rely on grain imports from Ukraine and Russia. In addition, the rise in food prices has put pressure on producers of renewable fuels based on feedstocks such as cereals and oilseeds, leading to a revival of the "food versus biofuels"debate. While many countries, such as the EU, the US, Indonesia and Malaysia, have blending mandates to ensure increased use of renewable fuels, policymakers are calling for a relaxation of biofuel blending mandates to increase global grain and vegetable oil supplies. These interdependencies with food demand and supply and thus food security, hamper the implementation of policy instruments to support sustainable production, because this requires comprehensive consideration of the entire nexus between development, food security and environmental objectives.

27.2 Developments in the Markets for Bio-based Products

Bio-based products are commercial or industrial goods (other than food or feed) composed in whole or in significant part of biological products, forestry materials, or renewable domestic agricultural materials, including plant, animal, or marine materials. These are products developed from biological materials, with the intent of replacing or enhancing products derived from non-renewable resources. The term Bio-based Product encompasses bio-based chemicals, bio-based plastics, enzymes, bio-based materials, and bio-fuels. Food and feed are excluded (OECD 2025).

Biomaterials are materials that can be used in a variety of applications, including packaging, textiles and construction, and are derived from renewable biological sources such as plants, animals or micro-organisms. Biomaterials include a wide range of materials, including bioplastics and biochemicals, and can be biodegradable or non-biodegradable, consisting of a single component or a combination of different components. Examples include natural fibres (e.g. cotton, hemp, flax), biopolymers (e.g. cellulose, starch, proteins) and composites (e.g. wood-plastic composites, bioplastics filled with natural fibres).

Bioplastics are a specific type of biomaterial used as an alternative to traditional plastics and are made out of polymers derived from non-petroleum, renewable biomass sources such as vegetable fats and oils, corn starch, straw, wood chips, sawdust, recycled food waste, etc. Here, the definition of European Bioplastic (2024) is applied, according to which a plastic material is defined as a bioplastic if it is either bio-based, biodegradable or features both properties. Examples of bioplastics include polylactic acid (PLA) from cornstarch or sugar cane, polyhydroxyalkanoates (PHA) from bacterial fermentation, polybutylene succinate (PBS) from corn starch or sugar cane, and cellulose acetate.

Biochemicals are chemical compounds derived from bio-based resources. Biochemicals can be used as intermediates or end products in a wide range of industries. They are also used as building blocks for various products, including bioplastics, biomaterials and chemicals (see ► Chap. 19). Examples include bio-based solvents (e.g. ethanol, butanol), surfactants and lubricants, bio-based acids (e.g. lactic acid, succinic acid), bio-based alcohols (e.g. glycerol, furfural) and biofuels.

Biofuels are liquid or gaseous transport fuels, such as biodiesel and bioethanol, produced from biomass. They serve as a renewable alternative to fossil fuels in the transport sector, with the aim of reducing greenhouse gas emissions and dependence on fossil fuels.

Compound annual growth rate (CAGR) is the average annual growth rate of a value, such as sales growth, taking into account the compound interest effect over a period of time and assuming constant growth.

In this section, we briefly introduce market developments for the bioeconomy as a whole and for selected bio-based products such as biochemicals, biofuels and bioplastics. In 2021, the EU bioeconomy accounted for a value added of € 728 million, of which the food, beverages and tobacco sector accounted for 36%, followed by agriculture (28%) and bio-based chemicals, pharmaceuticals, plastics and rubber (10.7%) (◘ Fig. 27.2 and Lasarte-Lòpez et al. 2023). More than 17 million people were employed in the EU bioeconomy sectors. 66% of the EU's biomass supply comes from agriculture, 34% from forestry and only 0.3% from fisheries. 58% of this biomass is used for food and feed, 21% for bioenergy and 21% for biomaterials (see ◘ Fig. 27.3).

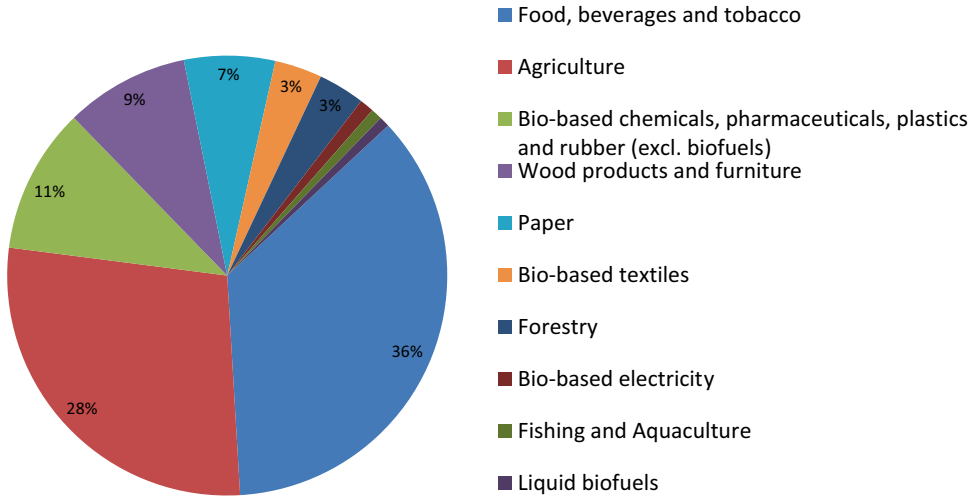


Fig. 27.2 Sectorial composition of the value added in the bioeconomy of the EU27 in 2021 according to NACE classification (Kuosmanen et al. 2020), based on data from Lasarte-López et al. (2023)

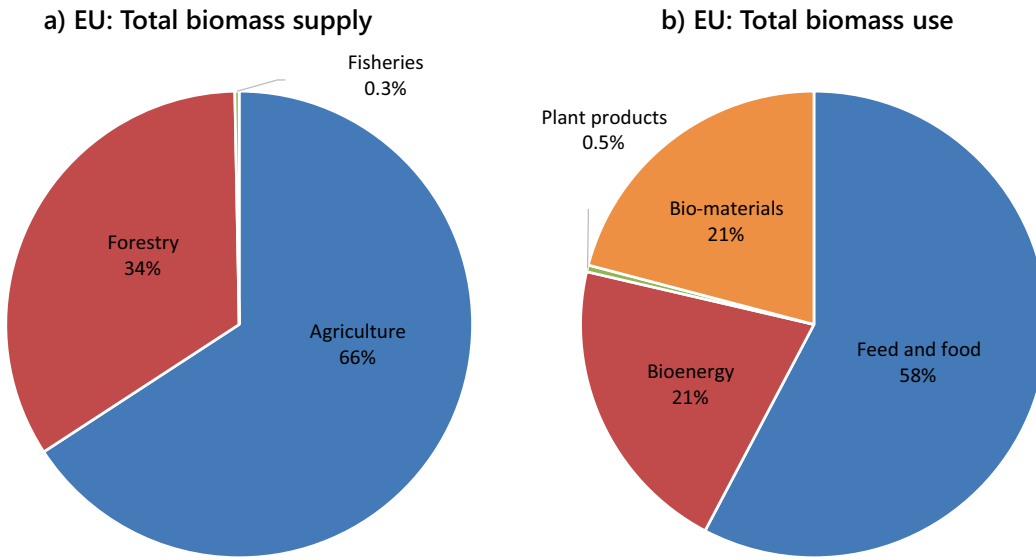


Fig. 27.3 EU biomass supply and use based on data from Kuosmanen et al. (2020)

27.2.1 Biofuels

First, we take a closer look at the biofuels market, which is one of the largest of the selected bio-based product groups and has been growing for more than three decades. Markets for the other two, biochemicals and bioplastics, are still under development and information on these is comparably scarce.

Global liquid biofuel production has continuously increased over the last three decades. Figure 27.4a shows the development of the world ethanol and biodiesel production from 2000 to 2022. In 2022, global biofuel production amounted to 162 billion litres, which corresponds to an increase of about 35% over the past 10 years. Ethanol production accounts for 75% of total biofuel production (OECD/

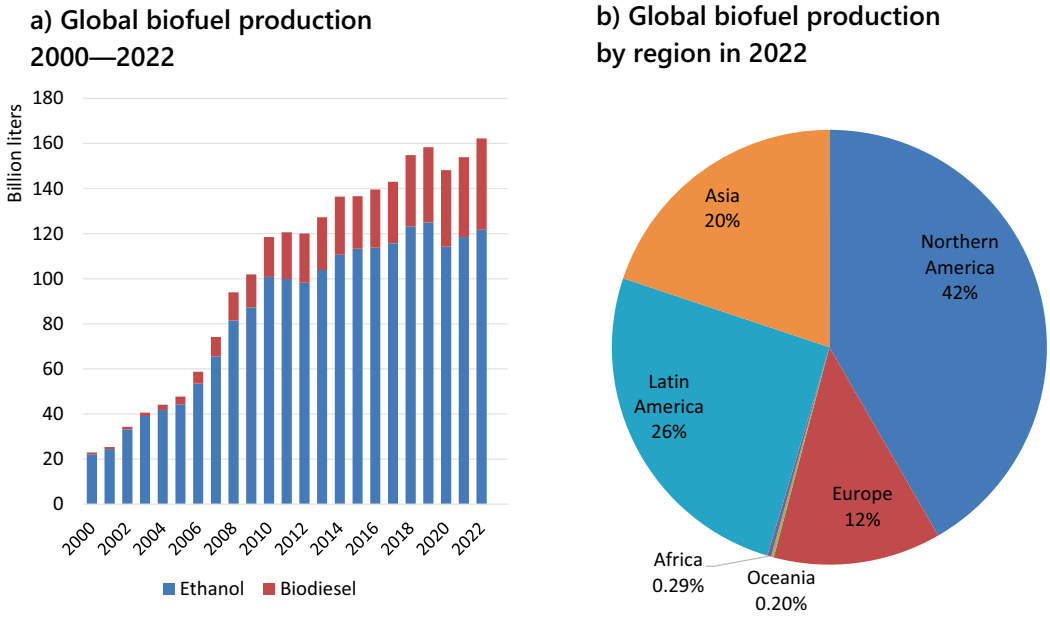


Fig. 27.4 Development and regional distribution of global liquid biofuel production based on data from OECD/FAO 2024

FAO 2024). In 2022, North America was the major producer of biofuels, followed by Latin America (including the Caribbean), Asia and the European Union (Fig. 27.4b). According to Gallagher (2008), around 1% of total global cropland was used for biofuel production in 2006. OECD/FAO (2024) predicts an increase in production of 30.7% for biodiesel and 20.6% for ethanol between 2022 and 2032.

As a result of the 1973 oil embargo initiated by the Organization of the Petroleum Exporting Countries (OPEC), which led to a dramatic increase in oil prices, Brazil started the production of ethanol from sugar cane to reduce its dependence on fossil oil. This move was facilitated by the low international sugar prices at that time and by Brazil's implementation of several policies promoting the further expansion of ethanol production. In 2009, Brazil produced around one third of global ethanol, only exceeded by the US with a share of more than 50%, mainly produced from corn (Janda et al. 2012). From about 10.9 million gallons of renewable ethanol in 2009, US production has increased to about 15.6 million gallons in 2022. Since 2010, the US has been a net exporter of renewable ethanol, resulting in a net trade of about 1.4 billion gallons, while Brazil has expanded renewable ethanol production from 6.6 million gallons (2009) to 7.4 million gallons (2022) (US Energy Information Administration 2024). According to ePURE, European renewable ethanol production in 2023 was 6.4 billion litres, of which around 86% was used as fuel, and 8.77 million tonnes of by-products such as distiller grains, corn germ or oil, of which 6.51 million tonnes were used as food or feed. The main feedstock used to produce renewable ethanol in the EU was corn (7.95 million tonnes, 48.3% of the renewable ethanol produced), followed by wheat (4.52 million tonnes, 24.8%), sugar (1.04 million tonnes, 10.4%), other cereals and starch crops (0.87 million tonnes, 5.3%) and lignocellulosic and other feedstocks (1.59 million tonnes, 11.2%). In 2023, the EU imported about 2084 million litres of renewable ethanol, mainly from Pakistan, the US, Brazil and the UK (ePURE 2023).

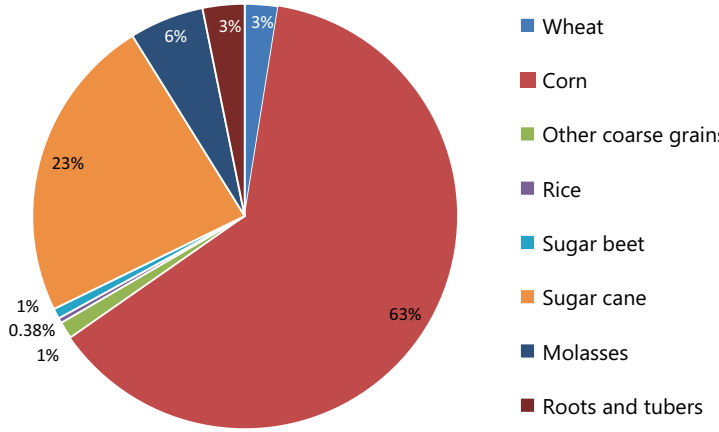


Fig. 27.5 Production of ethanol by feedstock use based on data from OECD/FAO (2024)

The shares of the different feedstocks in global renewable ethanol production in 2022 are shown in Fig. 27.5. Accordingly, corn (63%) and sugar cane (23%) account together for 86% of global ethanol production with other sources playing minor roles. The EU and Asia are the major producers of biodiesel (34% and 33%, OECD/FAO 2024). Global biodiesel production amounts to about 52 million tonnes in 2022, of which the EU accounts for 13.7 million tonnes (25%), the US 10.1 million tonnes and Indonesia 9.7 million tonnes (EBB 2023).

Biodiesel is mainly produced from vegetable oils, where the primary feedstock varies between regions. At the global level, palm oil accounts for 36%, soybean for 23% and rapeseed for 14%. While the US produced about 2.6 million gallons of biodiesel in 2023, mainly from soybeans (US EIA 2024), producers in Asia—particularly Indonesia (5600 million litres, 2018), Thailand (1560 million litres, 2018) and Malaysia (1245 million litres, 2018)—produced it predominantly from palm oil (Syafiuddin et al. 2020). Other feedstock used is, for example, coconut oil (Philippines) and used cooking oil (China, India, Japan). EU biodiesel production, mainly from vegetable oils (76%), particularly rapeseed (40%), is expected to grow by 1.5% per year, so that the EU will remain the world's largest producer of biodiesel, but with a declining share (from 30.7% to 28%) (EBB 2023).

Since the Russian invasion of Ukraine has begun, energy and food prices have surged globally. Countries made efforts to divert crops destined for renewable ethanol and biodiesel production to food (Esonye et al. 2023). As Ukraine is a major exporter of corn, sunflower, wheat and rapeseed, the war directly affects ethanol production from corn and wheat but particularly also biodiesel production, since almost all Ukraine's rapeseed and sunflower seed exports are used for biodiesel production (Kalentrik et al. 2014).

The conflict with food security, i.e. the expansion of land used to produce biomass for biofuels competing with land used and needed for food production, is a major challenge for sustainable biofuel production. Food prices may rise and food security, particularly in vulnerable countries, may be affected by the conversion of agricultural land from food crops to biofuels.

Figure 27.6 depicts the development in demand for biofuel production of the three dominant feedstocks corn, sugar cane and vegetable oil, over the period from 2000 to 2022. The figures highlight that the use of these agricultural products for biofuel production has continuously increased in terms of both absolute quantity and share in total

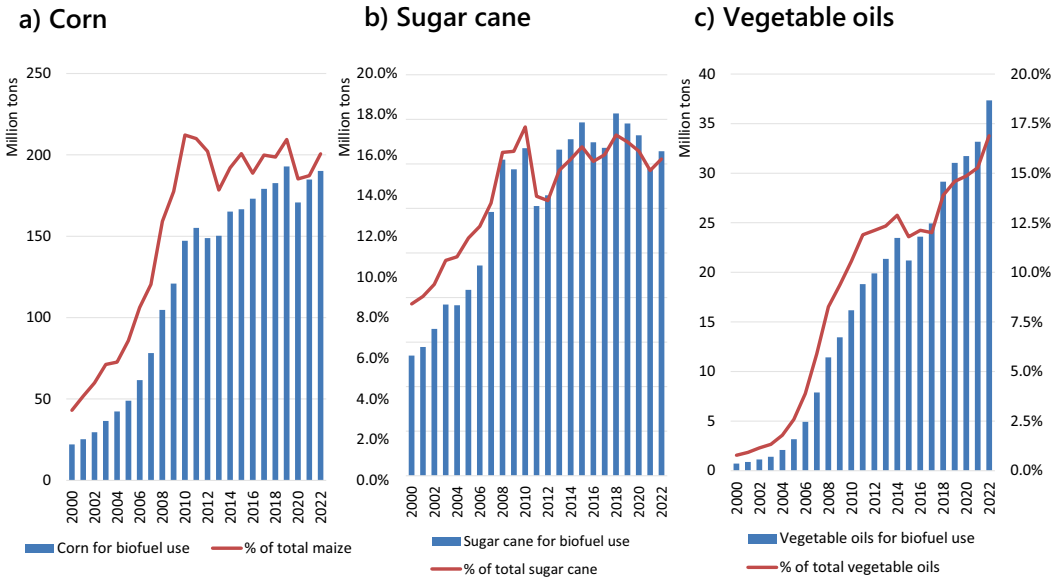


Fig. 27.6 Crop product demand for biofuel production based on data from OECD/FAO (2024). Note: Red line: % of total crop production, blue bars: biofuel use in tonnes

production of these commodities. The share of corn production used for bioethanol rose from 3% in 2000 to 16% in 2022. Over the same period, sugar cane use for bioethanol increased from 12% to 21% and vegetable oil use for biodiesel from 1% to 17%. However, the growth in demand for corn and sugar cane has slowed over the past decade, whereas it remains high for vegetable oils. Particularly, the graph for sugar cane highlights the food price spikes in 2007/2008 and 2011 and shows increased demand for biofuel use due to very high crude oil prices with a one-year lag. While a high crude oil price may increase the competitiveness of biofuels, it also increases the total production cost of biofuels. However, the extent differs between countries and crops used for production. Van Lampe (2007) assesses biofuel production costs by considering energy, processing and feedstock costs and subtracting the value of by-products. A simple indicator for the competitiveness of biofuels can be derived from the ratio of crude oil to biofuel feedstock prices. The demand for alternative fuels, such as biofuels, increases with rising crude oil prices. This, in turn, increases the input prices and demand for agricultural commodities, such as corn, rapeseed and sugar cane, and thereby raises their prices. Consequently, higher oil prices increase biofuel production and feedstock costs. Apart from the ethanol or biodiesel itself, biofuel production yields valuable by-products which have become important, especially as protein-rich animal feed supplements, such as distillers' grains from ethanol production or oilseed meals (Popp et al. 2016).

Figure 27.7 reveals that especially the price indices for cereals and vegetable oils are related to the crude oil index, whereas the sugar index's relation to the crude oil index is less obvious. During the periods of high crude oil prices in 2007/2008 and 2011–2014, the crude oil price rose more strongly and remained longer at a high level than the indices of the three biofuel feedstocks. The high oil price increased the competitiveness and economic viability of biofuels. By contrast, the Russia-Ukraine war in 2022 had a direct impact on both the price of crude oil (due to an oil export embargo against Russia) and the supply of the three most important biofuel feedstocks, of which Ukraine is a major exporter. Correspondingly, the resulting total effect on biofuel competitiveness was unclear.

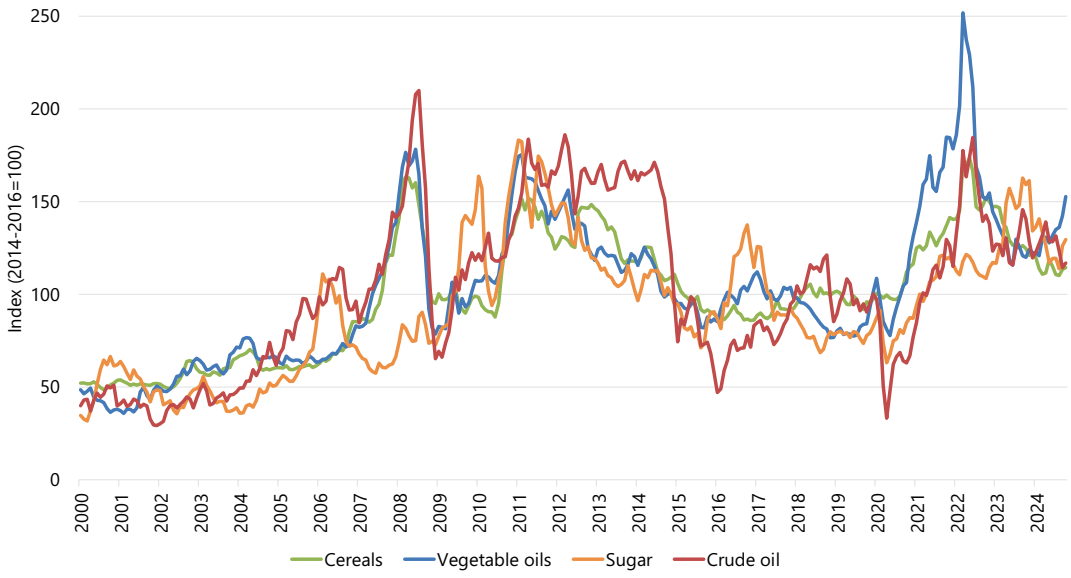


Fig. 27.7 Price indices for different agricultural commodity groups based on data from FAO (2024) and the average crude oil price from the World Bank (2024). Note: The FAO indices are weighted group averages. The crude oil price index is the simple average of three spot prices: Dated Brent, West Texas Intermediate, and the Dubai Fateh

27.2.2 Biochemicals

The markets for biochemicals, biopharmaceuticals and bioplastics are less developed than those for biofuels. They can still be considered as infant industries, but they could gain significant market acceptance in the future. Both the number of biochemicals produced from biomass and the range of products made from these biochemicals are very large.

The biochemicals market, which includes biodiesel, amino acids, fine chemicals, plant chemicals, antibiotics, dyes and pigments, is expected to grow at a compound annual growth rate (CAGR) of 10.6% over the period 2023 to 2032 (Fig. 27.8), with biodiesel accounting for the largest market share by type. Biochemicals are produced from a variety of feedstocks, including corn, sugar cane, sugar beet, wheat and cassava. Overall, the comparatively low production costs of these feedstocks make bio-based chemicals cheaper to produce than conventional chemicals produced from fossil resources. As governments put more emphasis on environmental issues, biochemicals are on the rise. Countries and industries are looking to renewable materials for long-term sustainable growth (MarketsandMarkets 2024; Precedence Research 2024).

Because of the range of products included in the biochemical sector, the OECD (2011) classifies the biochemical market according to the different segments of the chemical industry. In 2007, sales of chemicals made from bio-based feedstocks in the chemical industry amounted to EUR 48 billion, representing only a small fraction (3.47%) of total production (Festel 2010). In 2007, the EU-27, North America, including Canada, the USA, Mexico and Asia dominated the biochemicals market, accounting for more than 90% of total sales (OECD 2011). Pharmaceuticals, organic chemicals and cosmetics were particularly important. The EU is the most important player in the biochemicals market. In 2013, around 6% of all chemical products were bio-based. However, there are large differences at the level of the EU Member States. Denmark and Latvia reached biochemical shares of more than 35%, while France, Germany and the Netherlands only around 5%, and many

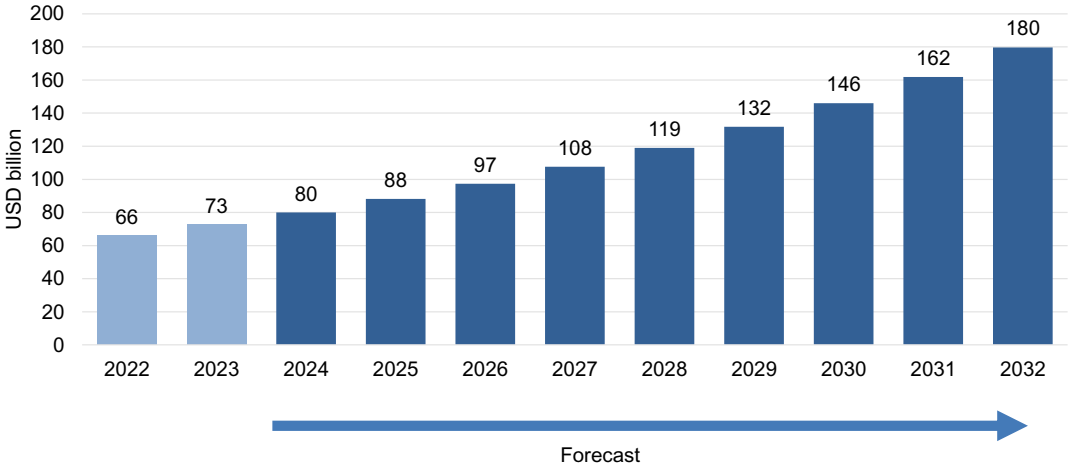


Fig. 27.8 Size and forecasted development of the market for biochemicals based on data from Precedence Research (2024). Note: Market values for the years 2024 to 2032 are based on forecasts

of the newer Member States even less (Piotrowski et al. 2016). According to Hatti-Kaul et al. (2007), the EU average was expected to rise to 20% by 2020. In the US, biochemicals account for less than 4% of total chemical sales. Asia is gradually increasing its market share.

In the EU28 (including UK) the total production of chemical product categories (including platform chemicals, solvents, polymers for plastics, paints, coatings, inks and dyes, surfactants, cosmetics and personal care products, adhesives, lubricants, plasticizers (and stabilizers for rubber and plastics) as well as man-made fibres) amount to a of total 156 million tonnes of which 3% can be classified as bio-based (Spekreijse et al. 2019). Platform chemicals (61 million tonnes), polymers for plastic (60 million tonnes) and coatings, inks and dyes (10 million tonnes of paints) account for more than 80% of total chemical production. Thus, platform chemicals and polymers for plastics are the largest categories of total chemicals produced in the EU. However, the share of bio-based products in these two categories (0.3% and 0.4% respectively) is the smallest in the EU chemicals market, while it is 9.7% for paints, coatings, inks and dyes (Fig. 27.9). This suggests an opportunity for development. Categories with high shares of bio-based production (50% and 44% respectively) are surfactants and cosmetics and personal care products. The fact that surfactants are largely composed of oleochemicals, which are typically considered to be bio-based, explains the remarkable market development for surfactants. The EU is a net exporter of bio-based polymers for plastics and lubricants, but a net importer of bio-based plasticizers and solvents. The EU is also a net importer of higher-consumption bio-based chemicals such as paints and surfactants. As the latter two categories are mainly based on oleochemicals derived from vegetable oils, the EU's dependence on third countries for vegetable oils could have a significant impact (i.e. a leakage effect) on developing countries where these feedstocks are typically sourced (Baldoni et al. 2021). A detailed description of the market for bio-based chemicals in the EU can be found in Spekreijse et al. (2019), while Spekreijse et al. (2021) compare fossil and bio-based value chains for bio-based chemical, plastics and pharmaceuticals.

Figure 27.10 shows the total feedstock use in 1000 tonnes (kton) per year in the EU28 for the production of bio-based products differentiated per application. In addition, Baldoni et al. (2021) estimated the land requirement for bio-based products (i.e. how much land is needed to produce a tonne of a bio-based product), which varies from zero to three hectares per tonne. Bio-based pro-

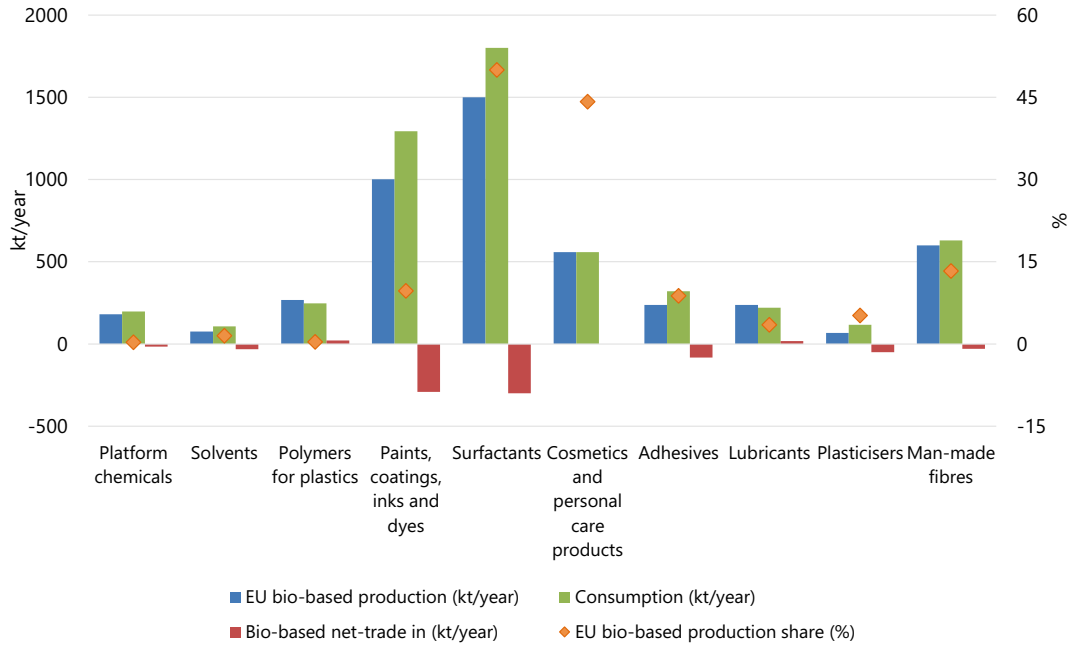


Fig. 27.9 EU production, consumption and net trade of bio-based chemicals based on data from Baldoni et al. (2021)

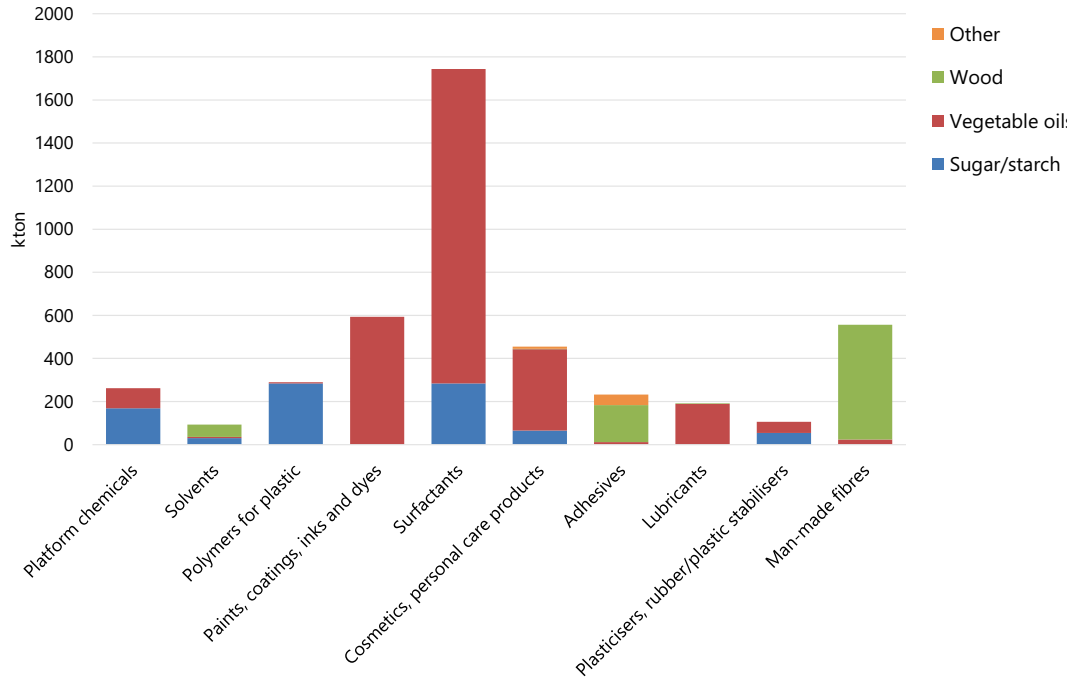


Fig. 27.10 EU biochemicals production by feedstock based on data from Spekreijse et al. (2019)

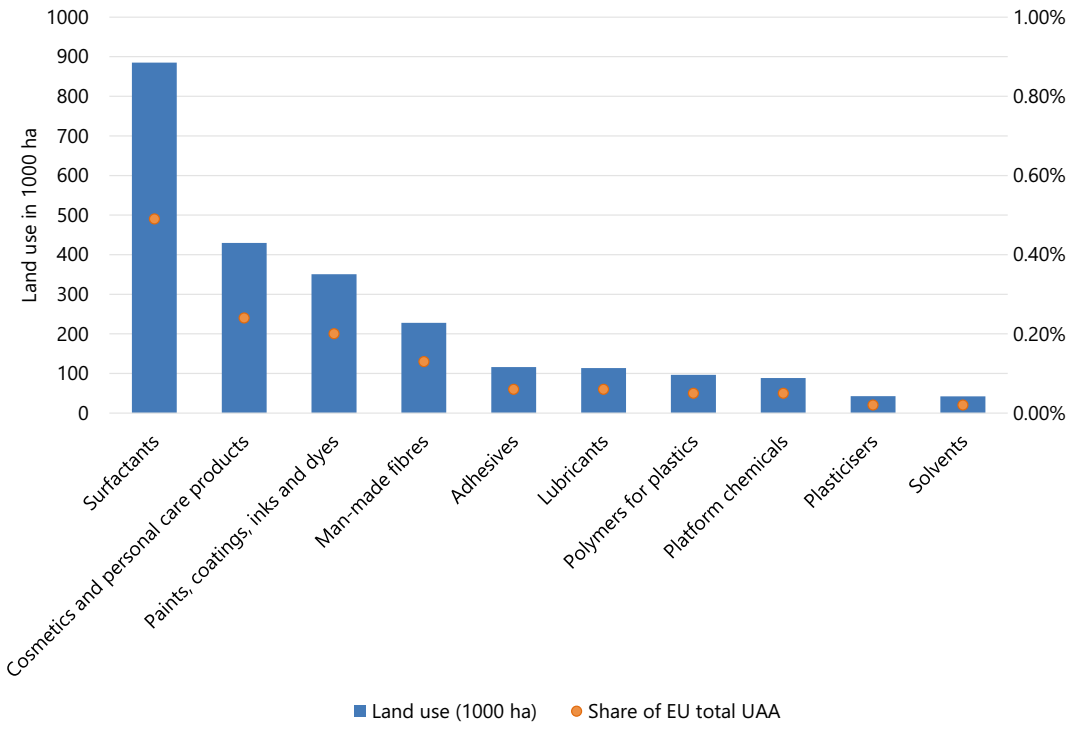


Fig. 27.11 Land use in hectares by application category based on data from Baldoni et al. (2021)

duction made out of waste or wood products tends to have the lowest land requirements, while, for instance, products made from oil crops such as glycolipids have the highest land requirements. Figure 27.11 shows that bio-based surfactants are the application category with the largest land use (i.e. how much land is used overall per production category), currently accounting for 0.49% of the total Utilized Agricultural Area (UAA). Cosmetics and personal care is the application category with the second largest estimated land use, followed by paints, coatings, inks and dyes and man-made fibres with estimated land use impacts of 0.24%, 0.20% and 0.13% UAA, respectively. All other remaining application categories have an estimated land use impact of less than 0.10% of the total UAA.

The EU is a major world player only for a few bio-based chemicals (Fig. 27.12). While the EU has a high share of world production for lactic acid (53.8%), succinic acid (46.0%) and furfuryl alcohol (13.3%), it has a low share for 1,3-propanediol (5.5%) and PLA (3.9%). According to Baldoni et al. (2021), prices seem to be higher in the EU. Looking at EU prices relative to world prices, EU prices are particularly high for acetic anhydride (+60%), furfuryl alcohol (+42%), ethylene glycol (+29%) and propylene glycol (+28%), while in 2 cases (furfuryl alcohol and succinic acid) the EU still accounts for a significant share of world production, despite the higher price. Only for ethyl acetate (17%), lactic acid (5%) and ethyl lactate (4%) EU producer prices are lower than world prices.

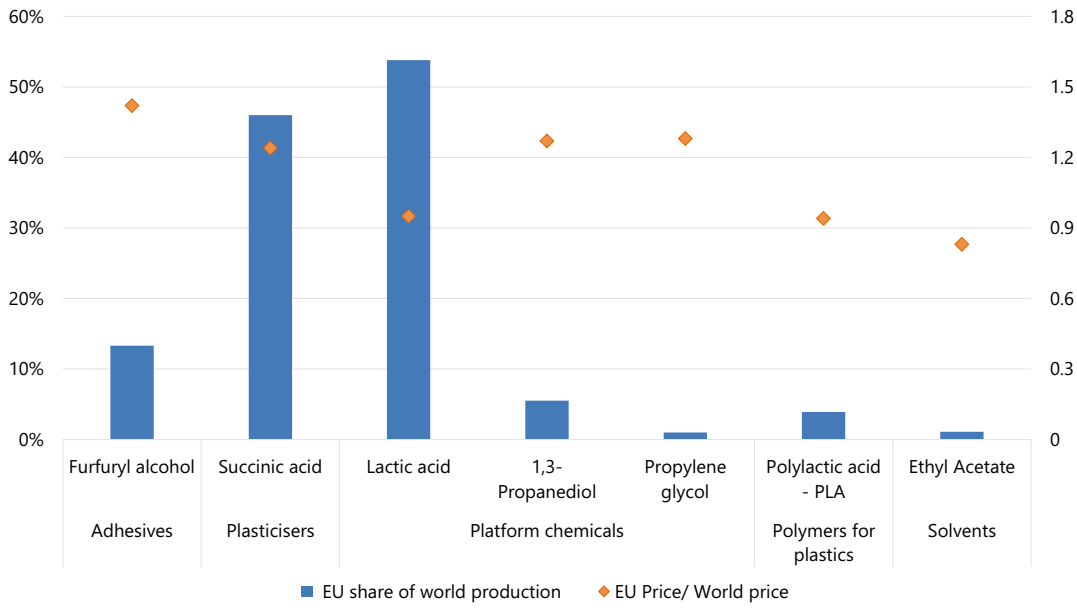


Fig. 27.12 EU share of selected specific bio-based chemicals based on data from Baldoni et al. (2021). Note: The EU share of world production is depicted on the left axis, while the price ratio is depicted on the right axis

27.2.3 Bioplastics

The market for bioplastics dominates the category of biomaterials. Bioplastics are plastics derived from renewable biomass sources, such as vegetable fats and oils, starches, cellulose, biopolymers and a variety of other materials.

In 2022, bioplastics accounted for only 0.5% of the total world annual plastic production of about 400 million tonnes (European Bioplastics 2023). Estimates indicate that the production capacities of bioplastics could increase from 1.8 million tonnes in 2022 to approximately 7.4 million tonnes in 2028 (European Bioplastics 2023). Bioplastic production includes non-biodegradable (0.949 thousand tonnes) and biodegradable plastics (0.864 thousand tonnes) is forecasted to significantly increase to 7432 thousand tonnes in 2028 of which 4605 thousand tonnes would be biodegradable.

The production and consumption of biodegradable plastics has increased over time, driven by the idea that they break down into carbon dioxide, water and biomass in a natural environment. Between 1995 and 2017, innovation in biodegradable plastics doubled, as measured by the number of patented inventions. More recently, concerns have been raised about the environmental impact of compostable plastics due to issues related to biodegradation in the natural environment, which has slowed the pace of innovation. Other reasons include the mixed environmental impact of biodegradable plastics made from bio-based polymers and the impact on the quality of recycled resources if collection and recycling conditions are not appropriate (OECD 2022).

The bioplastics market in 2016 and 2022 was clearly dominated by Asia (1.81 million tonnes in 2016; 0.92 million tonnes in 2022), followed by Europe (1.13 million tonnes; 0.59 million tonnes) and North America (0.97 million tonnes; 0.42 million tonnes) (European Bioplastics 2016, 2024). Figure 27.13 shows the regional market shares.

The global bioplastics market is estimated to reach a value of USD 15.57 billion in 2024 and continue to grow at a CAGR of 19.5%

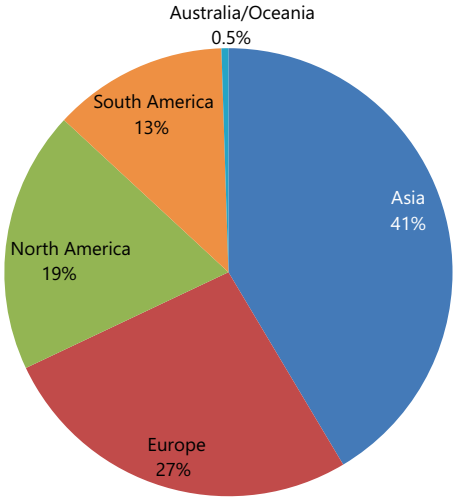


Fig. 27.13 Global bioplastics production capacity by region in 2022 based on data from European Bioplastics (2024), nova-Institute (2022)

from 2025 to 2030. The increasing use of bioplastics in the packaging industry (e.g. for the production of boxes, films and bags) is driving the global demand for bioplastics. The main drivers for market growth are the increasing restrictions on the use of single-use, non-biodegradable plastics in developed regions such as North America and Europe, and emerging economies in Asia Pacific. In addition, consumer preference for sustainable packaging and increasing landfill problems around the world are expected to drive the need for bioplastics in industrial, food & beverage and household care packaging (Grandview Research 2024b).

Europe, owing to stringent environmental regulations and pushing towards a circular economy, will account for the largest revenue share of 43.38% in the bioplastics market in 2024. Rising applications in various industries like textile, automotive and transport, packaging, consumer products and medical devices are expected to further boost the market. In the US, the bioplastics market is estimated to be worth around $2.6 billion in 2022, with around 60% used in packaging and over 50% biodegradable, and an expected CGAR of 19.3% to 2030 (Grandview Research 2024a). Increasing demand from various sectors, including the automobile industry and consumer goods, as well as advances in manufacturing infrastructure and rising disposable incomes, are expected to drive the growth of the bioplastics market in Asia. The market in the region is also expected to gain significant momentum in the coming years due to a shift in consumer preferences towards environmentally friendly materials. China's bioplastics market will witness significant growth over the forecast period due to the increasing demand for bioplastics in various applications, such as packaging, consumer goods and textiles (Grandview Research 2024a).

Figure 27.14 shows the development of the different bioplastic alternatives that exist for almost every conventional plastic material and corresponding application for the period 2019 to 2023 and the projected development until 2028. According to the projections, a significant increase in the production capacity of

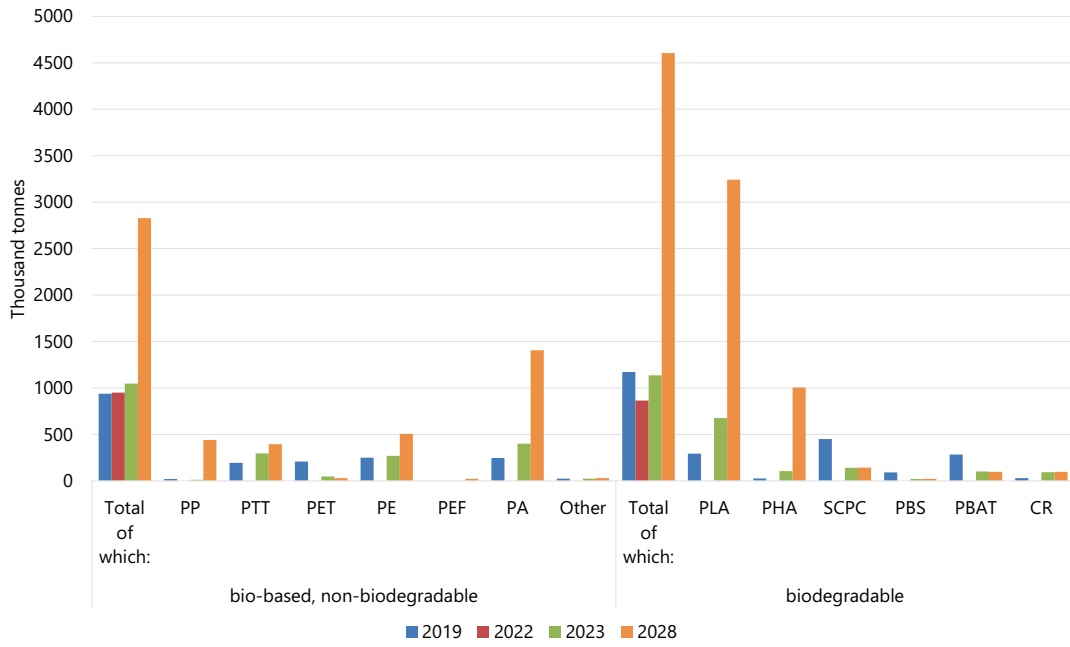


Fig. 27.14 The market for bioplastics in 2019, 2022 and projected for 2023 to 2028 based on data from European Bioplastic (2024)

polymers such as polylactic acid (PLA), PHAs (polyhydroxyalkanoates), PAs (polyamides) and a steady growth of polypropylene (PP) are expected over the next 5 years.

Within the bioplastics industry, bio-based Polylactic Acid (PLA) is the leading bio-based plastics product and grows faster than others. PLA is used mainly in packaging, but it also has a large number of other durable applications. After a period of stagnation, it reached around 550,000 tonnes in 2022 and has been projected to increase even faster in the nearer future, to around 3.24 million tonnes per year in 2028 (European Bioplastics 2023). Several traditional fossil-based plastics, such as PS (polystyrene) and PP (polypropylene), can be replaced by high-performance PLA grades.

The company "Nature Works" from the US and Thailand is a world leading supplier of biopolymers. In 2011, "Nature Works" holds a PLA market share of almost 80% (140,000 t from a total of 180,000 t per year), whereas the other producers had capacity varying between 1500 and 10,000 tonnes per year (Bioplastic Magazine 2012). As of 2025, a new manufacturing facility located in Thailand will provide additional production capacity of 75,000 tonnes of biopolymers (Nature Works 2024).

PHAs are an important family of polymers with a wide range of physical and mechanical properties, albeit produced for a long time, they are only now entering commercial production on a larger scale. The production capacity of these biodegradable polyesters is set to quadruple over the next 5 years (European Bioplastics 2023).

In 2022, bio-based non-biodegradable plastics, including bio-based PE (polyethylene), bio-based PET and bio-based PA (polyamide), account for around 50% (one million tonnes) of global bioplastics production capacity. Plans to increase bio-based PET capacity have not materialized to the extent predicted in previous years, while bio-based PE production is expected to continue to grow. Instead, the focus has shifted to the development of PEF (polyethylene furanoate), a new polymer that is expected to enter the market soon. PEF is an ideal material for beverage bottles because it is comparable to PET but is completely bio-based and has

superior barrier and thermal properties. Another polymer that will soon be commercially available is bio-based polypropylene.

Agricultural-based and ligno-cellulosic feedstocks are the main sources of bioplastics today. They are currently the most efficient and profitable option and stem from plants rich in carbohydrates (corn or sugar cane) and lignocellulosic biomass (such as agricultural residues, forest residues and perennial grass) not suitable for food or feed production. In 2022, global bioplastics production capacity was 2.2 million tonnes and required approximately 0.8 million hectares of land to grow the renewable feedstock, which is expected to increase to 2.9 billion hectares by 2027 (European Bioplastics 2024). The area needed to grow the feedstock for bioplastics production in 2022 represents 0.015% of the world's total agricultural area of 5 billion hectares. In 2022 (2008), 25% (18%) of the global agricultural area was used for food, 66% (71%) for animal feed, 4% (4%) for bioenergy and 2% (7%) for material use (Raschka and Carus 2012; European Bioplastics 2023).

Above, we have introduced the recent developments on the markets for bio-based products and how these developments are reflected in the demand for agricultural commodities, land use and prices. How does this additional demand for corn, sugar cane and vegetable oils (on top of food and feed demand) affect the market for agricultural commodities? To answer this question, we analyse supply and demand on the market for corn, exemplary for an input to the production of bio-based products.

27.3 The Market for Bio-based Resources and Products: Deriving Demand and Supply Curves

How supply and demand on a market interact and how they depend on and affect other markets is analysed using a market diagram. Here, we are going to use the corn market as an example for introducing the market diagram due to its omnipresence in all areas of the bioeconomy, i.e. food, feed, biofuels, bioplastics as well as biochemicals. For a comprehensive introduction to the theory of markets, the reader is referred to standard textbooks of microeconomics, e.g. Mankiw and Taylor (2023). In the market diagram presented in ◘ Fig. 27.15a, the horizontal axis represents the quantity demanded, whereas the vertical axis represents the price. The demand curve (D) shown in black depicts the relationship between the price for corn and the quantity of corn consumers are willing and able to buy at each particular price where—according to the law of demand—the quantity demanded depends negatively on the price. This normal, negative demand reaction to price increases is the result of two separate effects: (1) If the corn price increases, the consumer can afford less quantity of corn at the given income and thus demands less. This is the income effect. (2) When the price of corn increases, the consumer will look for alternative products similarly satisfying the need and substitute some of the corn consumption, for instance, with wheat. This is the substitution effect. Both effects will cause the consumer to buy less corn if its price increases, so that the total quantity of corn demanded will decrease. Usually, a demand curve in a market reflects the aggregate demand of all consumers in the market. In ◘ Fig. 27.15 we assume that consumer 1 (blue curve) represents the corn demand by food and feed producers, whereas consumer 2 (green curve) represents the corn demand by producers of for example biofuels and bioplastics. Both curves together add up to the total demand in the corn market. If the price for corn increases, both consumers want to buy less of it. The strength of the consumers' reaction to the price increase is measured by the price elasticity of demand. The price elasticity of demand measures by what percentage the quantity demanded decreases if the price increases by 1%. Note that the price elasticity of demand is a negative number, but the minus sign is often omitted for the sake of simplifying the discussion of the value, as is done in the discussion following. A price elasticity of demand equal to one means that a 20% increase in the price

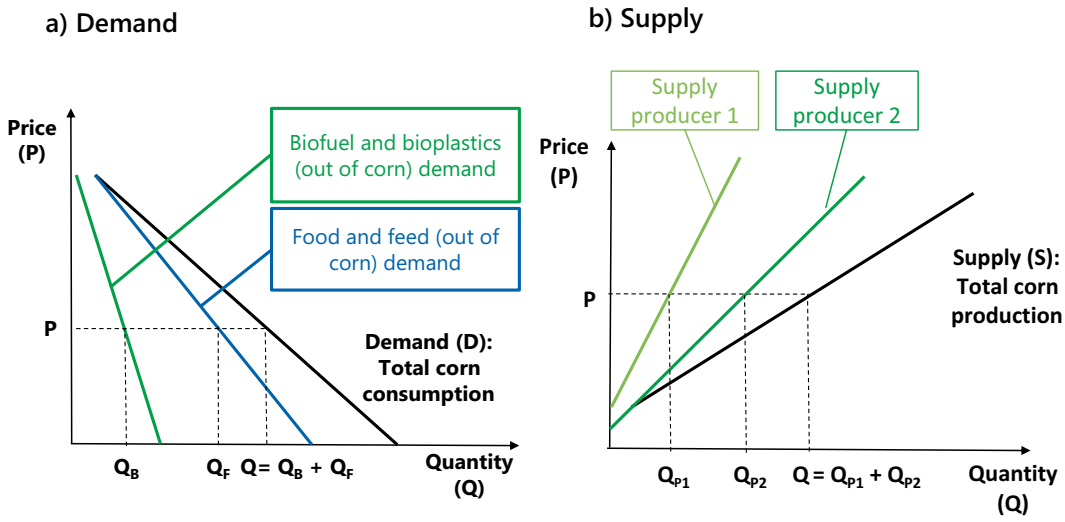


Fig. 27.15 Demand and supply functions

of corn, for example, leads to a 20% decrease in the quantity demanded. If instead the price elasticity of demand is less than one, the demand is called inelastic. The quantity demanded falls by less than 20% and the demand curve has a steeper slope. If the elasticity is greater than one, the demand is called elastic. The quantity demanded increases by more than 20% and the demand curve is flatter.

Figure 27.15b displays the supply side of the corn market in the same type of diagram. The supply curve (S) shown in black depicts the relationship between the price of corn and the quantity of corn that producers in the country are willing and able to supply, which applies as long as the price they receive for the next unit is higher than the cost of producing it (price greater than marginal cost). Usually, supply is positively related to the price due to factors causing production costs to increase with increasing level of production output, depending on the particular product market. This is illustrated by two examples. Increasing the production of corn could be achieved, for example, by allocating additional land or using more fertilizer. Both would increase the production costs of a tonne of corn: Commonly, all good quality, suitable land is already under productive use and thus the farmer would need to offer a higher land rental price than others to obtain additional land. Likewise, applying additional fertilizer increases the corn yield but the particular gain in yield per hectare from the next unit of fertilizer applied is the lower, the more fertilizer is already applied to the field (diminishing marginal product). Thus, the quantity of corn that can be profitably produced increases with the market price of corn and the quantity supplied to the market increases. The supply curve represents the aggregated supplies of all sellers, here supplier 1 and 2, just as the demand curve is the sum of the demand of all consumers. This simple example of a market is general and equivalently applies to the demand and supply of any other market, such as those for sugar, fuels or bioplastics. Analogous to the demand side, there is a price elasticity of supply which measures the percentage change in supply by producers in response to a 1% increase in the market price.

27.4 The Market for Bio-based Resources and Products: Determining the Equilibrium Price and Quantity

In the previous section, we have graphically analysed the demand and supply curves using the example of corn. Now, we combine

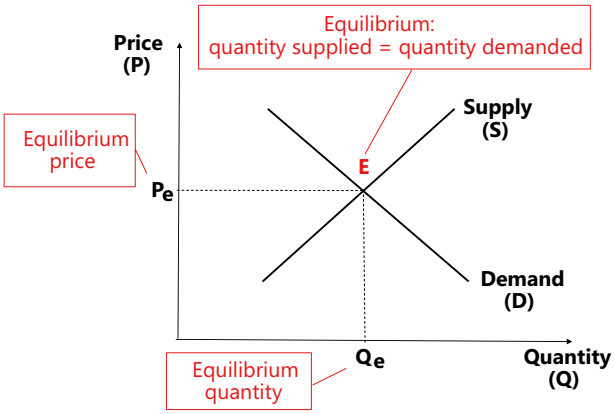


Fig. 27.16 The equilibrium of supply and demand

demand and supply curves in a market diagram to determine the equilibrium quantity and price at which a good is traded in the market. Figure 27.16 represents the market by combining the supply and demand curves in a single diagram. The market equilibrium (E) is the point at which the demand and supply curves intersect. This point defines the market price (equilibrium price) at which the quantity supplied on the market equals the quantity demanded, thus the price at which the market is cleared. In a competitive market, the market price automatically settles in the equilibrium due to the interactions between consumers and producers.

Let's consider again our corn example. Suppose that in the initial situation the market price for corn is higher than the equilibrium price. At this price, the quantity supplied is larger than the quantity demanded (excess supply or surplus). As a result, not all suppliers are able to sell their corn at the current price and they reduce their prices. At a lower price, consumers demand more corn and producers supply less. This process of lowering the price of corn and the corresponding reactions of buyers and sellers will continue until the quantity of corn supplied equals the quantity demanded, equivalent to movements along the demand and supply curves, respectively, towards the equilibrium point. Besides the market price, there are other factors that determine the quantities supplied and demanded, respectively. We can observe movements along the demand curve and shifts of the demand curve. Continuing the example, if the price for corn decreases, the result is an increase in the quantity demanded, which is equivalent to a movement along the demand curve. At the same time, the price decrease reduces the quantity of corn supplied and is equivalent to a movement along the supply curve.

By contrast, an increase (decrease) in the quantity demanded at a given price corresponds to a shift of the curve to the right (left), and analogously for the quantity supplied. What are the causes for such shifts in the demand and supply curves? Let us start with the demand side. Common factors that lead to a shift in the demand curve are changes in the prices of goods related to the observed good, income, tastes and preferences and expectations.

In our corn example, concerns about the climate impacts of fossil oil-based industries increase the demand for biofuels. This results in a shift of the demand curve for biofuels to the right and consequently, also in a shift to the right of the demand curve for the biofuel feedstock corn (change in preferences). Conversely, a decrease in the fossil oil price would lead to a decrease in biofuel demand and thus also decreases the demand for corn, shifting its demand curve to the left (change in the price of a good related to biofuels). From an economic perspective, biofuels are a substitute for fossil oil. Products are called substitutes if an increase in the price of one commodity (fossil oil) leads to an increase in

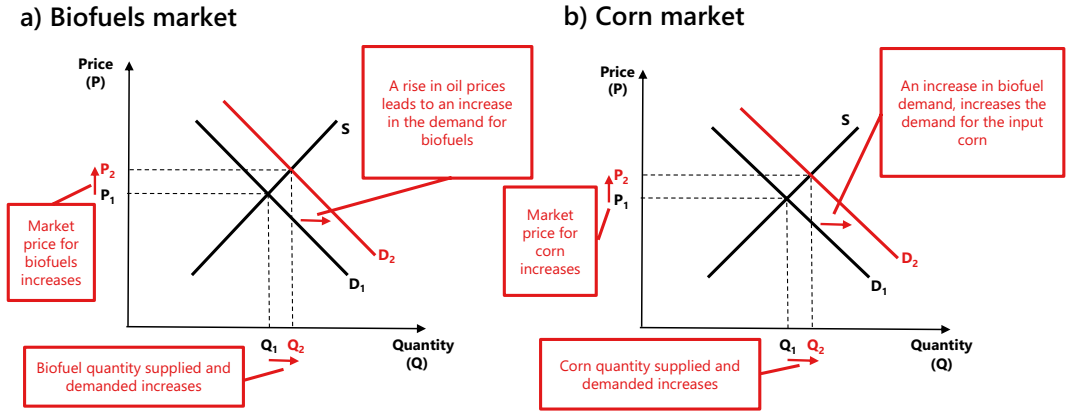


Fig. 27.17 Supply and demand effects on the resource market

the demand for the other commodity (biofuels). However, in other cases, an increase in the price of one commodity would lead to a decrease in the demand of another commodity, e.g. fossil oil and cars. Such products are called complements.

How are the equilibrium price and quantity on a market affected by a price increase of a related product? Figure 27.17 presents the effects of a rise in the fossil oil price on the market for biofuels (Fig. 27.17a) and on the market for the biofuel input corn (Fig. 27.17b). Due to the increase in the fossil oil price, the market price for fossil fuels also increases, so that biofuels become relatively cheaper and demand for biofuels increases at every price, indicated by the demand curve shifting to the right ($D_1 \rightarrow D_2$). At the initial biofuels price (P_1), demand now exceeds supply. This excess demand induces suppliers of biofuels to raise the price. Consequently, the increased oil price raises the equilibrium price for biofuels ($P_1 \rightarrow P_2$) and the equilibrium quantity of biofuels sold ($Q_1 \rightarrow Q_2$). An increase of the equilibrium biofuel quantity in diagram (a) raises the demand for its inputs such as corn. This is shown in diagram (b). At every price, the demand for corn is increased as represented by a shift of the demand curve to the right ($D_1 \rightarrow D_2$). This results in an increase of the equilibrium price and quantity for corn, which in turn affects biofuel producers. Shifts of the supply curve are usually caused by changes in input prices, technology or expectations. To produce biofuels, several inputs are required, among them corn.

If the price of corn rises, as in Fig. 27.18b, this increases the input cost of biofuel production and therefore reduces the quantity of biofuel supplied at every price, as represented by a leftward shift of the supply curve (Fig. 27.18a), whereas technological progress reduces the cost of biofuel production and shifts the supply curve to the right. If biofuel producers expect a further increase in oil prices and therefore decide to expand their biofuel production, the supply curve shifts to the right. Effects on the supply of inputs that cause increased input prices are, for example, a drought leading to a reduced corn harvest, an increase in the rental price of land, and an increase in the price of fertilizer (effects shown in Fig. 27.18b). The reduced supply of biofuels leads to an increase in the equilibrium price and a reduction of the equilibrium quantity (Fig. 27.18a).

When analysing the effects on the market for bio-based products and resources, we also need to consider the effects on factor markets, e.g. land. In the real world, we have to cope with a limited land supply. The options for gaining additional land area for farming via, for example, deforestation or polder landscape are limited. In addition, desertification and soil erosion cause loss of usable land. Therefore, if an increase in the demand and supply of bio-based products leads to an

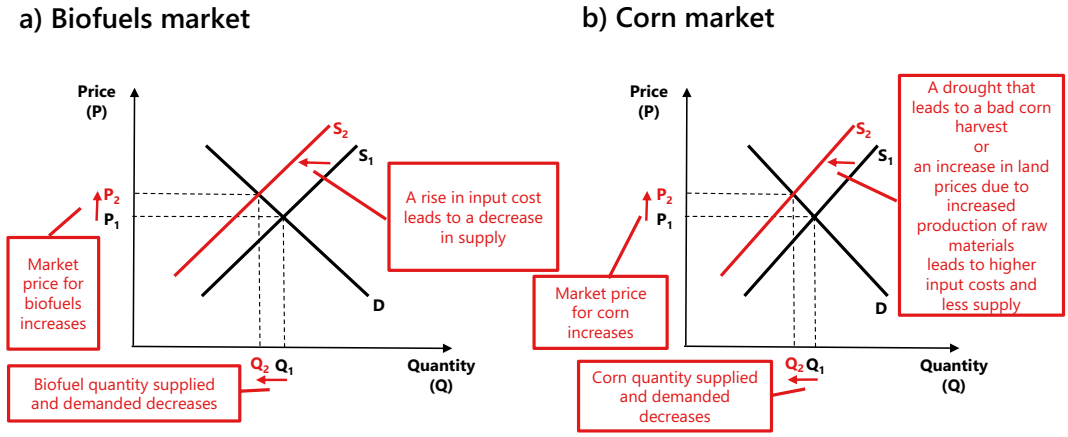


Fig. 27.18 Supply and demand effects on the market for bio-based products

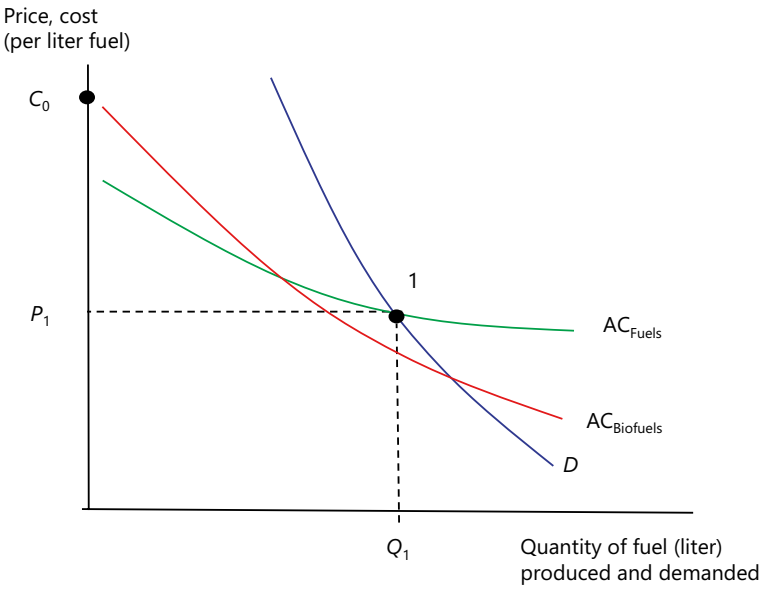


Fig. 27.19 Developing markets and the infant industry argument

increase in the amount of crops produced for the bio-based market, this is only possible by reallocating land from the production of food to the production of resources for non-food applications. This increase in the demand for land leads to an increase in the price of land, which increases input costs, making the production of bio-based products less cost-effective.

So far, we treated the markets for fossil oil, agricultural raw materials and bio-based products in the same way. However, as stated in the introduction, most of the bio-based products are relatively new so that the corresponding production processes often need substantial further research and development before the products eventually might become competitive with their established non-bio-based substitutes. Figure 27.19 shows the average cost curves for fossil fuel and biofuel production. Currently, Q_1 litres of fossil fuel are sold on the market at price P_1. At this price, the average cost curve for biofuels lies below the average cost curve for fossil fuel, implying that biofuels

potentially could be sold cheaper. However, the fossil fuel industry got established first and is able to sell fuels at price P_1, which is below the start-up cost of C_0 of the biofuel industry. Due to the current lack of experience and market share to benefit from economies of scale, the biofuels industry incurs high production costs and cannot compete in the fuel market at the moment. This provides a motivation for temporary support of the biofuel industry through the government—often referred to as the infant industry argument. Through the support (or protection) of the biofuel industry at its initial development stages, the industry can develop and reduce its production costs through the development of new technologies and economies of scale, so that it might be able to compete with the fossil fuel industry in the future. Another argument for government support of the biofuels sector could be made based on higher environmental costs fossil fuels may cause, which are not accounted for in their price. This will be discussed in a later chapter under the concept of externalities (see ▶ Sect. 28.2.1.1). However, the GHG and other environmental benefits of biofuels in comparison to fossil fuels are still under debate, as reviewed in Jeswani et al. (2020).

27.5 Policy Instruments to Support Bio-based Products

Carbon taxes for example, are used to discourage the production of energy from fossil fuels and thereby encourage the production of biofuels. This simple instrument provides for product group specific taxes and aims to correct a market failure (see ▶ Sect. 28.2.1) by putting a price on GHG emissions, e.g. the production of fossil fuels is taxed because of the high GHG emissions associated with their use. This means that a certain proportion of the price (ad valorem tax) or a fixed amount (specific tax) has to be paid per litre of fuel.

Blending mandates are a policy instrument to ensure sustainable market demand for renewable and/or low-carbon fuels/energy vectors. The scope of blending mandates is primarily focused on liquid fuels, but these policy instruments are also relevant for gaseous fuels.

27.5.1 Carbon Taxes

In the previous sections, we have introduced the drivers of and barriers to the demand and supply of bio-based products. Objectives such as sustainable development, energy security, independence from fossil fuels, food security, waste reduction and climate change mitigation might be promoted through increased production and use of bio-based products. However, the only recently developed bio-based products have a disadvantage in the market due to their high production costs compared to products already established in the market (see ◘ Fig. 27.19). Conventional products based on fossil energy sources (e.g. crude oil, natural gas or coal) have an advantage over renewable fuels/energy, because they have gained from economies of scale due to mass production and learning effects, which have decreased their production costs over time. However, the use of these products is associated with high GHG emissions that lead to additional cost for society through, for instance, increasing occurrences of severe weather events, melting ice caps and increasing air pollution. These external costs (costs incurred by others who do not participate in this specific exchange of goods), which correspond to the value of agricultural production losses, health costs, costs of destruction by storms and floods, and the like, are not covered by the market price of these products, leading to an inefficient allocation of resources, i.e. a market failure. In light of these reasons, governments push the development of bio-based products as outlined in the introduction to this chapter. This is done with the intention of correcting the market failures associated with the utilization of fossil energy

sources and to establish an enabling environment for renewable alternatives. This should, in turn, enable these industries to mature and become competitive. To this end, governments introduce various policy instruments which promote the development of better technologies, increase the production quantity and thus the market share, and discourage the use of fossil fuels. Technological progress and economies of scale would then lead to a decrease in production costs and consequently increase the competitiveness of bio-based products. The comparison of the policy landscape of different bio-based products clearly reveals that the policies implemented to support bioenergy and liquid biofuels are the most advanced.

Biochemicals and biomaterials are found to be at a relative disadvantage because many of the policies applied to support biofuel and bioenergy production reward the use of biomass in these industries. According to the Renewable Energy Policy Network for the twenty-first century (REN21), nearly all countries worldwide (146 countries) apply policies to support the provision of renewable energies (REN21 2016). Most of them established bioenergy targets. In general, countries use manifold ways and policies to support biofuel production, e.g. establishing mandatory targets for the share of bioenergy in total energy use (more than 70 countries), applying policy instruments to support the production of biofuels (more than 100 countries), and imposing policy instruments which improve market access for imports of biofuels (more than 50 countries) (OECD 2014). A large number of policy instruments have been applied to stimulate bioenergy and biofuel production. In this section, we provide a general but brief overview of applied instruments to support bio-based products, particularly used for bioenergy and biofuels, and explain their economic rationale using the example of energy and carbon taxes.

Different instrument types are applied to support bio-based products. One distinction can be made between direct policy instruments, e.g. tariffs and subsidies on different (bio-based) products either domestically produced or traded, and indirect policy instruments, e.g. environmental taxes (carbon tax) or voluntary agreements. Direct policy instruments can either be provided to support renewable products, e.g. a subsidy on the production of bio-based products or a subsidy on agricultural products, such as corn, sugar or grains, to enhance the production of biomass or a tariff on the imports of bio-based products to support domestic producers. Governments provide subsidies across the entire biomass value chain to facilitate suitable conditions for bio-based product deployment. By contrast, indirect policies are mainly applied to fossil-based products by taxing these products to account for their negative external effects on the environment. This will be further explained instantly. All these policies are price-driven, e.g. in the case of a subsidy on bio-based products, the policy drives a wedge between the market price and producer price, so that the producers achieve a price higher than the market price. Feed-in tariffs serve as another example for creating price-driven incentives that are often applied in the renewable energy market. Producers of renewable energy can feed in the full production of green electricity at fixed prices. This policy provides specific support to producers of renewable energies, usually for a limited period. Specifically, the producer price for renewable energies equals the market price for energy plus the feed-in tariff rate, so that producers of renewable energies are paid a cost-based price for their energy supply that exceeds the fossil energy source-based price. Governments also promote the use of bio-based products, particularly biofuels, through excise tax reductions or exemptions that decrease the price paid by consumers.

27.5.2 Economic Rational of Policy Instruments

What is the underlying economic rationale behind a policy instrument, such as energy and carbon taxes, that imposes additional costs on the use of fossil energy sources, such as oil, natural gas and coal, in proportion to

the amount of carbon these resources contain? The additional costs associated with the utilization of fossil energy sources are passed through to the price of the final good, such as fuels, electricity or any goods that use these sources intensively. The policy instrument corrects the market failure by incorporating these additional environmental costs into the market price. Thereby, it modifies the incentives for producers and consumers such that the quantity produced and consumed is decreased. Figure 27.20 presents the effects of a carbon tax and shows how this policy instrument stimulates the production of biofuels. Let us assume that all energy products based on fossil fuels are taxed by an ad valorem carbon tax t that drives a wedge between the market price P_M and the producer price P_S equivalent to the size of the tax.

$$P_s = P_M\left(1+t\right) \tag{27.1}$$

On each unit of energy from fossil fuels sold on the market, producers have to pay the tax. Consequently, they receive less money per unit of output and reduce their supply on the market, which in turn leads to a market price increase. In panel (c) of Fig. 27.20 we analyse the effects of the tax on the fuel market, considering both the supply of fossil fuel and biofuel. S^1_{TF} represents the total supply of fossil fuels and biofuels together $\left(S^1_{FF}+S_{BF}=S^1_{TF}\right)$, whereas D_{TF} shows the total demand on the fuel market. The supply curve is upward-sloping, indicating that the supply of fuel increases as the market price increases. The demand curve is downward sloping showing that a price increase leads to a decrease in fuel demand. In the equilibrium (intersection of S^1_{TF} and D_{TF}) at the market price P_M the quantity Q^1_{TF} is sold on the market of which Q^1_{FF} are fossil fuels and Q^1_{BF} are biofuels. What happens when the government decides to impose a carbon tax? This tax affects the fossil fuel producers, because they pay now a tax per unit of output based on fossil fuels. Therefore, the supply curve of fossil fuels shifts to the left in panel (a) of Figure 27.20, reflecting that at every price producers sell less fossil fuel due to the tax.

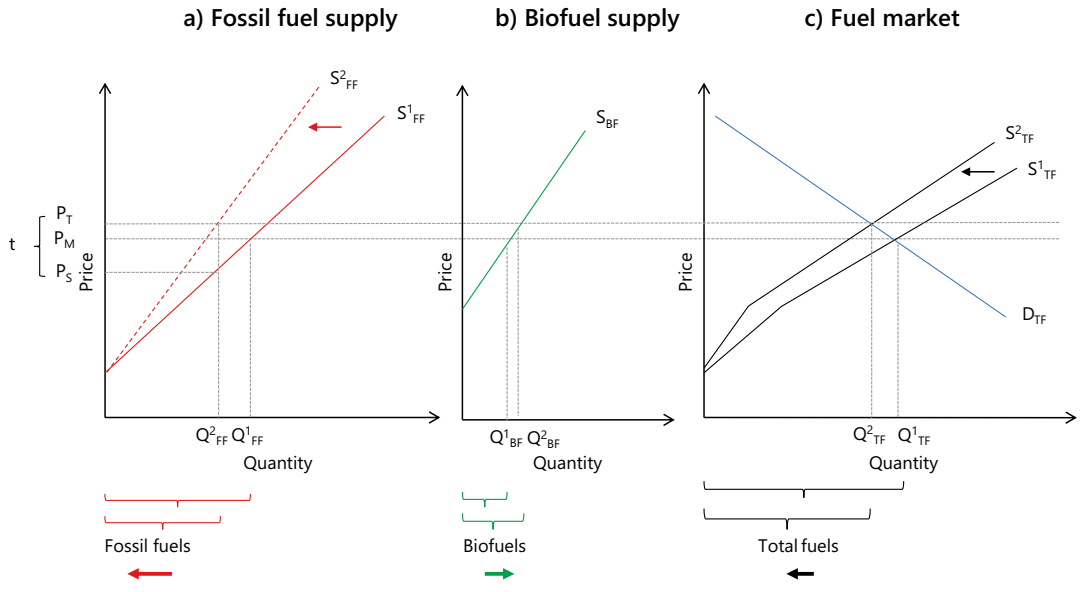


Fig. 27.20 Effects of a carbon tax on fossil fuel

However, the tax does not directly affect biofuel producers. Consequently, the biofuel supply curve in panel (b) of Fig. 27.20 does not change. In accordance with the change in panel (a), the total fuel supply curve in panel (c) also shifts to the left $\left(S_{TF}^{2}\right)$. At any market price for fuel, less quantity is supplied. The new market equilibrium reveals a decrease in the quantity of fuels supplied and demanded at a higher price. However, at this higher price biofuel producers sell a higher quantity of biofuels to the market, thereby increasing the share of biofuel relative to fossil fuel quantity as a result of the implementation of the carbon tax.

27.5.3 Other Policy Instruments

After discussing the economic rationale of a price-driven policy, we will now briefly introduce other types of policies that are also frequently imposed in the markets for bioenergy and biofuels. An example for a quantity-driven policy is, e.g. a blending mandate that defines a specific share of biofuels in transport fuel sold on the market. This policy is relatively cost-neutral for the government. However, it increases the demand for biofuels at the expense of final consumers due to the higher production costs of biofuels. Also, (tradable) green certificates provide quantity-driven incentives to increase the production of bio-based products. They are based on a quota-like mechanism that obliges producers to produce a specified fraction of their supply from renewable resources. These instruments are successfully applied to support bioenergy, e.g. low-carbon energy. In addition to price- or quantity-driven policy instruments, governments provide other budgetary support measures such as investment subsidies and new technology support. These subsidies are available in a large variety of different designs. Examples are funding for capital investments associated with a new project, or subsidized loans/interest rates or grants for production facilities. The objective is to enhance the efficiency of biomass utilization for the production of bio-based products, thereby increasing the supply and reducing production costs. Another measure is support provided to research or rural development.

Why is the amount of support provided to biofuels much higher than the amount provided to biochemicals and biomaterials? According to OECD (2014), the share of crude oil used for energy production exceeds 90% in most countries. In addition, simpler and a smaller number of standards is applied to biofuels compared to biochemicals. Consequently, controls on the chemicals market are much higher, which increases the number of obstacles that new products must overcome to gain market access. Plastic is a material used for a large variety of purposes, which in turn increases the number of expectations on the properties of plastics compared to fuel (OECD 2014). This considerable diversity in standards, applications and expectations associated with biochemicals and biomaterials presents a significant challenge to the design and implementation of support policy instruments. By contrast, the development of all three product groups depends on the same resource (biomass) and related technologies.

Excursus 27.1 Economic and Environmental Impacts of Future Expansion of Bio-Chemicals, Plastics and Pharmaceuticals in the EU

In ▶ Sect. 27.2, we have described current market developments and medium-term prospects for biofuels, bioplastics and biochemicals, while we have discussed the impacts of subsidies and carbon taxes in ▶ Sect. 27.5.1 to support the production of bio-based commodities. In this excursus, we now want to look at the impact of imposing such policies to boost the production of bio-based commodities. To indicate the likely benefits and costs of further expanding the production of bioplastics and biochemicals, this excursus highlights the main findings of a study by Philippidis et al. (2023).

Philippidis et al. (2023) use a global economic model (see ▶ Sect. 42.2.1 for more information on modeling) to examine the impact of EU investments targeted at increasing the production volume of bio-based chemicals, pharmaceuticals and plastics by two, three and five times by 2050, compared to the BAU scenario (A so-called business-as-usual (BAU) scenario is a scenario that assumes a continuation of trends with regard to economic, demographic, technological, political and biophysical drivers, for example of production and consumption). The study models these investments as subsidies for bio-based chemicals, pharmaceuticals and plastics, which are financed by higher taxes on all EU users of traditional chemicals, plastics and pharmaceuticals. This study, therefore, examines the market and environmental impacts of expanding bio-based production in the future.The results show that the expansion of bio-based chemicals, pharmaceuticals and plastics production up to 2050 affects sectoral output and GDP (see ◘ Fig. 27.21). EU bioeconomy production increases significantly, but this is accompanied by a small decrease in non-bioeconomy activities and a slight decrease in overall EU economic growth (−0.2% to −0.9%) compared to the BAU in 2050. Demand for raw materials such as crops, forest products and residues increases due to the growth of bio-based production.

These developments are leading to strong increases in the demand for land in the EU between 1058 km^2 and 4625 km^2 (see ◘ Fig. 27.21), driving up agricultural land rents, which in turn is driving up the prices of crops, livestock, conventional biofuels and food. The study shows that higher demand for food and other commodities puts pressure on food markets, making food less affordable. This increase in land and other input costs also makes bio-based chemicals more expensive in the EU.

Philippidis et al. (2023) highlight that land use in the EU is increasing, mainly due to industrial demand for cereals and sugar crops. Arable and pasture land in the EU increases by 0.11% to 0.48%, while land used for energy crops and forests decreases slightly. Globally, agricultural land increases by 0.03% to 0.14%, driven by increased biomass imports into the EU.

The impact on GHG emissions in 2050 is mixed. Agricultural emissions increase due to changes in land use, but industrial CO_2 emissions decrease due to chemical decarbonization leading to cleaner production. Overall, EU GHG emissions increase slightly (0.08% to 0.36%), but rising demand for food-based commodities increases agricultural emissions outside the EU, while higher chemical exports help reduce emissions in non-EU markets.

Sustainability Pillar	Indicator		Twofold volume (constant prices) rise	Threefold volume (constant prices) rise	Fivefold volume (constant prices) rise
Economic Pillar	Output changes (%) vs BAU in 2050	Crops	0.55	1.12	2.32
		Primary agriculture	0.65	1.33	2.71
		Forestry	0.53	1.10	2.35
		Residues	0.45	0.96	1.99
		Energy crops	-0.13	-0.23	-0.39
		All biofuels	1.71	2.35	8.24
		Bioeconomy	2.22	5.21	11.91
		Non bioeconomy	-0.15	-0.29	-0.56
		EU real GDP	-0.19	-0.40	-0.86
Environmental Pillar	Land areas, km^2, vs BAU 2050	Arable	1.058	2.226	4.626
		Pasture	966	1.904	3.770
		Forestry	-105	-213	-425
		Energycrops	-2	-4	-7
	All emissions, $MtCO_2e$, vs BAU 2050	Agriculture, Fish, Forestry	3.38	6.86	13.79
		Industry	-1.06	-1.78	-2.80
		Total	2.14	4.66	10.06

Worsening — Improving

Fig. 27.21 Selected EU sustainability indicators for bio-based production support compared to BAU in 2050 based on data from Philippidis et al. (2023)

27.6 Conclusions

This chapter provides a brief introduction to the market for selected bio-based products that may become increasingly important in the future. Future global challenges will lead to increased demand and supply of bio-based products. In addition, this market is closely linked to the demand and supply of primary agricultural commodities and thus to food security. We introduce market diagrams representing the demand and supply functions for bio-based products to show how the market equilibrium price is determined. We use these diagrams to analyse the impact of supply and demand shocks on the market for bio-based products, but also on the market for agricultural commodities and fossil fuels.

The currently still high production costs of the relatively new bio-based products compared to the well-established conventional products, which are often based on fossil fuels, put bio-based products at a disadvantage. In addition, the prices of conventional products do not account for the additional environmental costs they cause, such as high carbon emissions. This leads to a market failure that is equivalent to an inefficient allocation of resources. Politicians use these two arguments as the main justification for implementing policies to support bio-based products. We provide a brief overview of selected policy instruments and illustrate the impact of carbon taxes on prices, supply and demand in the biofuels market using a market diagram.

Think critically about what weight should be given to the cultivation of crops for food versus the cultivation of crops as feedstock for bio-based products. You might then consider the following perspectives: rich versus poor countries, food-importing versus exporting countries, and future food security versus environmental sustainability.

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Questions

1. Name and discuss reasons why the production of bio-based products has gained importance in recent years?
2. Explain how high crude oil prices influence the demand for biofuels?
3. What are the challenges on the market for bio-based products?
   (a) Explain driving and limiting forces for the supply of bio-based products using one example for each.
   (b) Explain driving and limiting forces for the demand of bio-based products using one example for each.
4. The demand for bioplastics is expected to considerably increase in the future.
   (a) How would this increase in the demand for bioplastics affect the market price and quantity sold of bioplastic material? Please use a market diagram to illustrate and explain the results.
   (b) In addition, the government aims to support the production of bioplastics. Please explain and discuss appropriate policy instruments the politicians might introduce.
5. Assume that the bioplastics industry is able to considerably decrease its costs for producing bioplastics due to technological change.
   (a) How would this affect the supply of bioplastics? Please use a market diagram to show and explain the effects.
   (b) Bioplastics are produced from starch. How would therefore an increase in the production of bioplastics affect the market for wheat, corn and potatoes? Is there empirical evidence for the effect?
   (c) What would be potential effects on prices and supply of food products and thus food security?
6. Governments often use the infant industry argument to justify the introduction of policy instruments to support relatively new industries such as biofuel producers. Please explain and discuss this argument using biofuels as an example.

Answers

1. The production of bio-based products has gained importance due to their environmental benefits, including reduced greenhouse gas emissions, biodegradability and reliance on renewable resources. Economically, they diversify inputs and thus decrease the dependency from fossil inputs, create rural jobs and drive innovation. Government policies and incentives, such as subsidies, blending mandates, CO_2 taxes and bioeconomy strategies, further support their development. Rising consumer demand for green, eco-friendly and biodegradable products has also fueled their growth. Technological advancements in biotechnologies have improved efficiency and expanded product offerings, while global commitments to sustainability align with their adoption.
2. High crude oil prices increase the cost of fossil fuels, making biofuels a more competitive and attractive alternative for energy. As biofuels are often produced from renewable resources, they provide a cost-effective option when fossil fuel prices rise. This economic advantage boosts demand for biofuels, particularly in sectors like transportation where fuel costs are significant. Additionally, higher oil prices can encourage governments and industries to invest in biofuel production as part of strategies to reduce dependency on volatile fossil fuel markets.

3a. Driving Force:

- Technological Advancements: Innovations in biotechnology, such as enzy-

matic conversion, have made it more efficient to produce bio-based products. For example, advances in the production of bioplastics like polylactic acid (PLA) have reduced costs and increased scalability, driving their adoption in packaging and consumer goods.

Limiting Force:

– Feedstock Availability: Limited access to sufficient and sustainable raw materials can constrain production. For instance, the reliance on corn for bioethanol production can face challenges due to competition with food supply and fluctuations in agricultural output caused by droughts or other climate impacts.

3b. Driving Force:

– Consumer Preference for Sustainability: Growing awareness of environmental issues drives demand for eco-friendly alternatives. For example, the demand for biodegradable bioplastics has surged as consumers and businesses seek to reduce plastic pollution and align with sustainability goals.

Limiting Force:

– Higher Costs Compared to Fossil-based Products: Bio-based products often have higher production costs, making them less competitive. For instance, bio-based fuels like biodiesel can struggle to gain market share when fossil fuel prices are low, as consumers opt for cheaper conventional alternatives.

4a. The graph should illustrate how an increase in demand for bioplastics affects the market. Initially, the market is in equilibrium where the supply and the initial demand curves intersect, determining the initial price and quantity. When demand rises, the demand curve shifts outward (from "Initial Demand" to "New Demand"), creating a new equilibrium with a higher price and a larger quantity sold. This demonstrates that higher demand leads to both increased market prices and greater production/sales of bioplastic materials.

4b. Governments can implement various policy instruments to support the production of bioplastics, ranging from financial incentives to regulatory measures. Below are some possible strategies:

– Production Subsidies: Governments can provide financial support to manufacturers to offset production costs, making bioplastics more competitive with conventional plastics. For example, subsidies for purchasing bio-based feedstocks or for building bioplastic production facilities can lower barriers to entry.
– R&D Funding: Investments in research and development can drive technological advancements, improving production efficiency and cost-effectiveness.
– Mandates and Quotas: Legislating minimum bioplastic content in certain products, such as packaging or single-use items, can drive demand and encourage industry growth.
– Bans on Conventional Plastics: Phasing out or banning fossil-based single-use plastics creates a market for bioplastic alternatives. For example, banning traditional plastic straws, cutlery and bags can encourage the switch to biodegradable bioplastics.
– Labeling Standards: Requiring clear labeling of bioplastic products ensures transparency, helping consumers identify eco-friendly options and boosting market demand.
– Carbon Taxes: Taxing the carbon emissions from fossil-based plastics increases their cost relative to bioplastics, making the latter more attractive.
– Education and Awareness Campaigns: Informing consumers and businesses about the benefits of bioplastics can increase acceptance and demand.
– Import Tariffs on Fossil-based Plastics: Increasing the cost of importing conventional plastics can boost domestic bioplastic production.

5a. The graph should illustrate how a decrease in cost affects the market for bioplastics. Initially, the market is in equilibrium where the supply and the initial demand

curves intersect, determining the initial price and quantity. When cost decreases, the supply curve shifts outward (from "Initial Supply" to "New Supply"), as producers can sell more at each price, creating a new equilibrium with a lower price and a larger quantity sold. This demonstrates that lower cost leads to production expansion and lower market prices and larger production and consumption of bioplastic materials.

5b. Bioplastics are often produced from crops rich in starch, such as wheat, corn and potatoes. An increase in bioplastics production from starch crops can impact these agricultural markets as follows:

Increased bioplastics production raises demand for starch-based feedstocks:

- Higher Prices: Increased competition for these crops can drive up their market prices. This can affect food, feed and industrial users, leading to potential price hikes in related industries like animal feed or processed foods.
- Reallocation of Resources: Farmers may shift more land to cultivate starch crops, reducing supply for other crops and potentially altering agricultural land use patterns.

Supply-Side Adjustments.

- Expanded Production: Higher crop prices may incentivize farmers to increase the production of wheat, corn and potatoes. This could eventually balance the supply-demand equation but may come at the cost of environmental concerns, such as deforestation or increased use of fertilizers.
- Food Security Concerns: Diverting staple crops to industrial use might strain food availability in regions already vulnerable to food insecurity, intensifying debates about "food versus fuel" or "food versus bioplastics."
- Research on biofuels, which similarly rely on corn, shows that industrial demand can significantly influence agricultural markets. For example, studies have found that ethanol production in the U.S. drove up corn prices during the biofuel boom in the late 2000s. Increased demand for biofuels also contributed to the food price spike in 2007/08.

5c. Increased Demand for Agricultural Feedstocks: Lower production costs could make bioplastics more competitive with conventional plastics, potentially leading to higher demand for agricultural feedstocks (e.g. corn, sugarcane or other biomass) used in bioplastic production.

- Effect on food prices: Higher demand for these crops may drive up their prices, leading to increased costs for both food products directly made from these crops and those indirectly linked through feed (e.g. livestock).
- Effect on food supply: Farmers might allocate more land to cash crops for bioplastic production, potentially reducing the land available for food crops.
- Effect on Food Security: In regions already facing food insecurity, land use shifts to production of industrial crops for the production of bioplastics could exacerbate shortages by reducing local food availability and increasing reliance on imports, which might not be affordable for all.

6. The infant industry argument posits that new or emerging industries may require temporary protection and support from the government to develop and compete with established market players. This support typically comes in the form of subsidies, tariffs on foreign competitors or research and development incentives. The idea is that these measures help the industry achieve economies of scale, improve technologies and enhance efficiency until it becomes competitive in the global market.

- Biofuel production is a relatively new industry compared to traditional fossil fuels. Governments often justify using the infant industry argument to support biofuels for several reasons:
- Initial high costs: Producing biofuels, particularly in the early stages, tends to be more expensive than fossil fuels due to smaller production scales, less mature technology and supply chain inefficiencies. Without support, biofuel producers

might struggle to compete with the established, cost-efficient fossil fuel industry.
- Economies of scale: As biofuel production scales up, the cost per unit can decrease significantly. Government policies (e.g. blending mandates or subsidies) can help ensure sufficient demand to achieve these economies of scale.
- Positive externalities: Biofuels can provide environmental benefits, such as reduced greenhouse gas emissions and decreased dependence on finite fossil resources. Supporting the industry can align with broader climate and energy security goals.
- Market failures: Existing fossil fuel industries often benefit from sunk investments, established infrastructure and political influence. Government intervention can help level the playing field for biofuels to address these imbalances.

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Economics for a Sustainable Bioeconomy—Theory and Policies

Franziska Schuenemann, Marius Boesino, Pranav Patil, and Alina J. Rossa



Fig. 28.0 Economics for a sustainable bioeconomy—theory and policies. (© Universität Hohenheim, Uta Rometsch) (► https://doi.org/10.1007/000-hv9)

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At the centre of economics lies the question of how best to allocate scarce resources. This section, therefore, addresses the challenges and limitations posed by resource scarcity in the bioeconomy, a field where the optimal allocation of limited productive resources is crucial for achieving sustainability across economic, social, and environmental dimensions. Economics, as a discipline focused on resource allocation, provides a range of analytical tools for designing sustainable pathways. Several economic approaches contribute unique insights relevant to bioeconomy actors, including consumers, producers and policymakers. Welfare economics focuses on maximizing social welfare by relying on market mechanisms; environmental economics examines market failures, particularly those involving externalities and public goods, and offers policy solutions. Ecological economics advocates for a circular bioeconomy that respects planetary boundaries, and climate and energy economics explores the bioeconomy's potential to mitigate climate change, with a particular emphasis on biofuels and their associated trade-offs. Together, these perspectives outline a multifaceted economic framework essential for advancing a sustainable bioeconomy.

Learning Objectives

After studying this section, you will…

- …be able to describe the basic concepts of welfare economics and derive an efficient allocation in a market economy (see ► Sect. 28.1).
- …be able to explain the problem of market failure in case of externalities, discuss and show graphically how to internalize external effects and explain why property rights are important to ensure efficient and sustainable use of goods (see ► Sect. 28.2.1).
- …be able to describe different types of policy instruments that can achieve efficient allocations and evaluate which are best in which instances (see ► Sect. 28.2.2).
- …be able to describe the economics of climate change and the role of the bioeconomy to mitigate emissions (see ► Sect. 28.3).
- …be able to explain the production and the trade-offs of biofuels and to interpret the controversy around indirect land use change (see ► Sect. 28.4).

► Chapter 1 discussed in detail the challenges and limitations around resource scarcity in the bioeconomy. The scarcity of productive resources and how best to allocate them has traditionally been at the centre of the science of *economics*. Through this focus, economics brings the ideal tools to analyse the best pathway to achieve a bioeconomy that is sustainable in all three dimensions. There are several strands of economics that approach the question of resource allocation from different angles. All of them have important implications for actors in the bioeconomy, including consumers, producers and the government. These include:

- welfare economics, which studies the allocation of resources to maximize social welfare or overall well-being under the premise that markets know best
- environmental economics, which studies the problem of market failure through externalities and public goods, as well as policy instruments to correct these problems
- natural resource economics, which deals with the optimal allocation of non-renewable (e.g. land, fossil resources) and renewable resources (e.g. forest, fisheries, biomass) to ensure sustainability
- international economics to determine the role of international trade of resources
- ecological economics, which aims at reconnecting the economy and the environment within planetary boundaries through a circular bioeconomy and
- climate and energy economics, which concerns the role of the bioeconomy for climate change mitigation and adaptation, especially with a view to biofuels and their synergies and trade-offs

Some of these strands have already been covered in previous chapters, i.e. natural resources economics and economics of primary production in ▶ Chap. 16, international economics, trade and markets in ▶ Chap. 27, and the circular bioeconomy in ▶ Sect. 3.3. In the next subsections, we will therefore focus on studying welfare economics (see ▶ Sect. 28.1), environmental economics (see ▶ Sect. 28.2) and climate and energy economics (see ▶ Sect. 28.3).

Excursus 28.1: The Economy and the Environment

The challenges and limitations around resource scarcity in the bioeconomy derive from the inherent interconnections and interdependencies between the economy and the environment. The economy is dependent on environmental service flows from nature, which are also often called ecosystem services. These include the provision of natural resources, which directly affects resource availability, nature's function as a waste disposal that is severely affected through greenhouse gas emissions, amenity services such as those provided by enjoying biodiversity and life-support functions through the biosphere and atmosphere that ensure we can live on the planet earth. How large the demand of the global or local economy for these ecosystem services actually is depends on the size of the population, the affluence with respect to economic growth or income and which kind technologies the economy is using, e.g. very efficient or inefficient technologies.

28.1 Welfare Economics and the Role of Markets for Resource Allocation

As the name welfare economics suggests, this branch of economics studies how best to allocate scarce resources so as to maximize social welfare. This is the case if allocations are economically *efficient* and socially optimal. Welfare economics does not only consider natural resources but all productive resources, including labour and capital.

This leads to the four major questions of welfare economics. Given the available resources in an economy

- What goods are produced?
- In which quantities?
- Which combinations of resource inputs are used in production?
- How are those goods distributed between consumers?

Thereby, welfare economics provides an analytical framework for analysing whether markets or government interventions can improve social welfare. For instance, it can help to evaluate equity and distributional impacts of policies and interventions related to land use or social safety nets for communities affected by bioeconomic developments.

28.1.1 Efficient Allocation of Resources

A central focus of economics is the analysis of the efficient distribution of scarce resources that maximizes well-being of individuals, companies and the society as a whole. In welfare economics, an allocation of resources is considered efficient when it is not possible to make one or more persons better off without making at least another person worse off. This allocation of resources is also called a Pareto optimum and fulfils three criteria: Efficiency in consumption, efficiency in production and product-mix-efficiency.

▪ Efficiency in Consumption

Efficiency in consumption refers to a situation where consumers allocate their resources (such as income or time) in a way that maximizes their utility from the goods and services they purchase. ◘ Figure 28.1 shows an

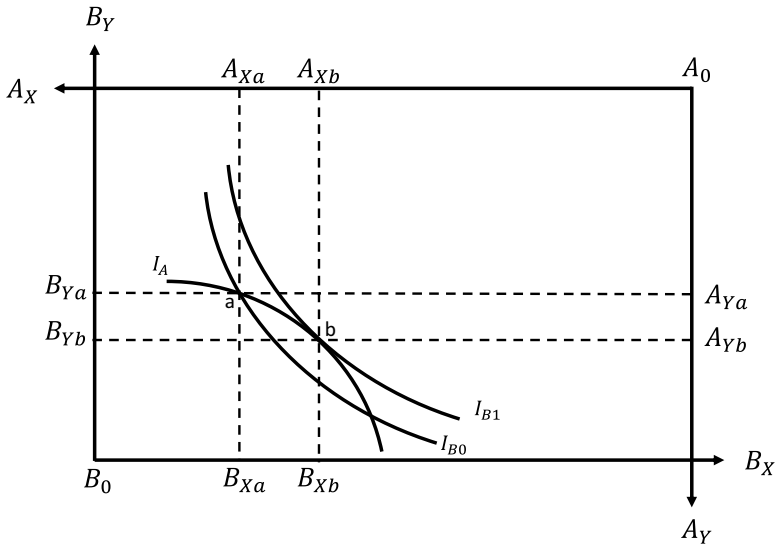


Fig. 28.1 Edgeworth-Box for the consumption of two goods (X,Y) by two consumers (A,B) represent the indifference curves of the consumers. Efficiency in consumption is achieved for allocation of goods at point b (tangency point). (Source: Own illustration based on Perman (2003, p. 107))

Edgeworth box for two consumers A and B. In the Edgeworth box, the indifference curves for different consumption bundles of the goods X and Y are drawn. At the origins A_0 and B_0, the consumers do not consume any of the goods. Moving horizontally/vertically farther away from the origin increases the consumption of X/Y for the respective consumer. As the overall availability of X and Y is constant, an increase in consumption of one of the goods for A comes along with a decrease in consumption of the good of B (and vice versa). On each indifference curve for the consumers, I_A and I_B, the utility from the consumption of the different bundles of the goods is equal. The farther away an indifference curve from its origin, the higher the utility of the respective consumer. For a Pareto optimal allocation of the goods X and Y it must not be possible to make one or more persons better off without making at least another person worse off. At point a, this condition is not fulfilled as consumption bundles to the right on I_A would keep the utility of consumer A constant but increases the utility of consumer B (shift to a higher indifference curve). Thus, graphically, Pareto optimality is met at the tangency point b of the indifference curves of the consumers A and B. At this point the marginal rates of utility substitution (MRUS)—the rate at which a consumer is willing to substitute one good for another while maintaining the same level of utility—of the two consumers are equal.

Efficiency in Production

Efficiency in production refers to the optimal use of resources in the production process to maximize output while minimizing waste, costs, or resource use. It is achieved when a firm or economy produces goods and services using the least amount of inputs (such as labour, capital and raw materials) for the maximum possible output. For the example of the production of two goods X and Y, Fig. 28.2 shows an Edgeworth box with the isoquants, i.e. the constant output levels of X and Y for different combinations of input bundles of capital (K) and labour (L). At the origins X_0 and Y_0 no capital or labour is assigned to the production of the goods. Isoquants farther away from the origin represent a higher output level of the respective good. Moving horizontally/vertically farther away from the origin increases the use of capital and labour for the production of the goods. As the overall availability of capital and labour is constant, an increase in the use of capital or labour for

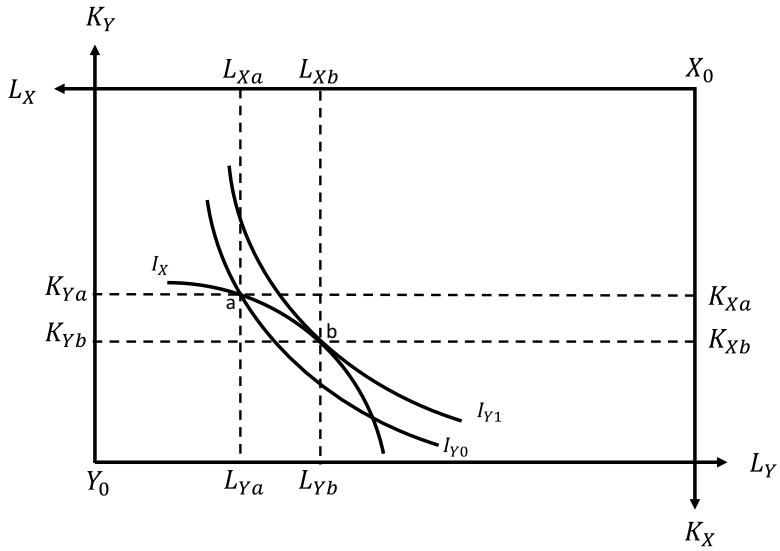


Fig. 28.2 Edgeworth-Box for the production of two goods (X,Y) using capital (K) and labor (L) as inputs. and show the isoquants, constant output level of X and Y, for different combinations of K and L. Efficiency in production is achieved for production of goods at point b (tangency point). (Source: Own illustration based on Perman (2003, p. 108))

the production of one good is met by a decrease in the use of the respective input for the production of the other good. At point a, levels of capital and labour used for the production of the goods is not optimal as moving along I_X to the right keeps the output level of X constant but the output of Y could be increased by the change in allocation of the input factors (shift to a higher isoquant). The highest achievable isoquant for the production of Y, given the output level of X, is reached at point b, where the marginal rates of technical substitution (MRTS)—the rate at which one input factor can be substituted for another while keeping the same level of output—for the production of the two goods X and Y are equal.

Product-Mix Efficiency

Product-mix efficiency refers to a situation in which an economy, firm, or producer is allocating resources in such a way that the combination of goods and services produced maximizes overall welfare or profit. It implies that resources are being used in the best possible proportions to meet consumer preferences or market demand. The latter is determined by the condition for efficiency in consumption. To realize the supply of the respective quantities of the goods, these need to be produced by the economy for which certain inputs are needed. Fig. 28.3 shows the production possibility frontier, which repre-

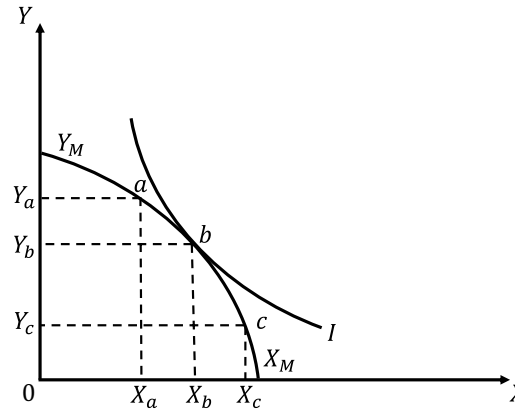


Fig. 28.3 Graphical representation of the product-mix-efficiency condition. Optimality is achieved at point b, where the indifference curve of the representative consumer is tangent to the production-possibility-frontier. (Source: Own illustration based on Perman (2003, p. 112))

sents all combinations of the production of two goods, X_M and Y_M, exploiting the available input factors (for example capital and labour). Given that the MRUS of the consumers are equal when efficiency in consumption is fulfilled, the consumers can be treated as having the same utility function and indifference curve *I*. The slope of the production possibility frontier is called marginal rate of transformation (MRT), which corresponds to the rate at which the output of good X can be turned into Y by shifting capital or labour from the production of one good to the other. At points a and c, the allocation of capital and labour to produce the two goods is not optimal as the utility of the consumers would be lower (on an indifference curve closer to the origin) compared to point b. At this tangency point of the indifference curve and the production possibility frontier MRUS equals MRT, and product-mix efficiency is fulfilled.

28.1.2 The Role of Markets in Resource Allocation

Most economies rely on markets to organize production and consumption. Markets allow buyers and sellers to interact, leading to price formation and efficient distribution of goods and services. In an ideal market, several conditions must be met for efficient resource allocation:

1. All markets are perfectly competitive: In a perfectly competitive market, there are many buyers and sellers, each small enough relatively to the market size such that no single buyer or seller can influence the price of goods or services. In consequence, both buyers and sellers accept the market price which is determined by supply and demand for the goods or services.
2. All economic agents (consumers and producers) have perfect information: Both buyers and sellers have full knowledge of product prices, quality and availability. This ensures that neither buyers nor sellers can exploit information asymmetry.
3. No externalities: There are no external effects (positive or negative) on third parties from the production or consumption of goods. All costs and benefits are reflected in the market price. Externalities are explained in ▶ Sect. 28.2.1.1.
4. All goods and services are private goods, and property rights are fully assigned: Goods and services being private assures that producers have an incentive to supply goods that they can sell exclusively to paying consumers. By having assigned property rights, owners bear the costs and enjoy the benefits of providing the good or service, and are thus incentivized to manage it efficiently.
5. All economic agents maximize their utility or profit: Consumers aim to get the most satisfaction or happiness (utility) from their limited income. By maximizing utility, consumers make choices that best reflect their preferences, ensuring that resources (goods and services) are allocated in a way that meets their needs. Firms aim to maximize profits by minimizing costs and increasing revenues. This pushes firms to produce goods as efficiently as possible.

Under these ideal market conditions, the two main theorems of welfare economics hold:

- **First Main Theorem of Welfare Economics**

If all firms maximize their profits and all households maximize their utility, a general market equilibrium is also a Pareto optimum.

- **Second Main Theorem of Welfare Economics**

For each Pareto optimal allocation, there exists an initial distribution of incomes and a price vector under which the desired Pareto optimum can be implemented as a market equilibrium through redistribution.

28.1.3 Market Equilibrium as a Pareto Optimum

To proof the first Main Theorem of Welfare Economics it needs to be shown that efficiency in consumption, efficiency in production and product-mix efficiency are fulfilled. Therefore, consider the following characterization of an economy: There are two households A and B with Incomes I^A and I^B that maximize their utility from the consumption of two goods x_1 and x_2, which are produced by 2 firms maximizing their profits. As production factors, the firms use capital (K) and labor (L). The two goods and inputs represent all existing goods and resources in the economy. The production factors are privately owned such that $p_K K + p_L L = I^A + I^B$, where p_K and p_L are given factor prices. The distribution of resource ownership is externally given, i.e. incomes I^A and I^B are exogenous. Furthermore, it is assumed that all agents have perfect information, and the market faces perfect competition with no market entry barriers.

First, the households i want to maximize their utility from the consumption of the two goods $U_i\left(x_1^i, x_2^i\right)$ subject to their budget constraint $p_1 x_1^i + p_2 x_2^i = I^i$. This maximization problem can be solved using the Lagrangian method. Thereby, partial derivatives from the Lagrangian function are taken.

$$L\left(x_1^i, x_2^i, \lambda\right) = U_i\left(x_1^i, x_2^i\right) + \lambda\left(I^i - p_1 x_1^i - p_2 x_2^i\right)$$

These first order conditions are:

$$\frac{\partial L}{\partial x_1^i} = \frac{\partial U_i}{\partial x_1^i} - \lambda p_1 = 0 \tag{28.1}$$

$$\frac{\partial L}{\partial x_2^i} = \frac{\partial U_i}{\partial x_2^i} - \lambda p_2 = 0 \tag{28.2}$$

$$\frac{\partial L}{\partial \lambda} = I^i - p_1 x_1^i - p_2 x_2^i = 0 \tag{28.3}$$

By solving (28.1) and (28.2) for λ, the equations can be set equal and through rearrangement it is achieved that:

$$\frac{\frac{\partial U_i}{\partial x_1^i}}{\frac{\partial U_i}{\partial x_2^i}} = \frac{p_1}{p_2}$$

The term on the left-hand side is the formula for the MRUS, which is for both households equal to the relation of the prices of the two goods. From the assumption that the market faces perfect competition, it follows that both households are price takers, such that in consequence $\text{MRUS}_A = \text{MRUS}_B$ and efficiency in consumption is fulfilled.

Second, the two firms want to maximize their profit (revenue minus costs). For firm 1 producing good x_1 this means

$$\max_{x_1, K, L} p_1 x_1 - p_K K - p_L L$$

Subject to a certain production function for the good: $F_{x_1}(K, L) = x_1$. The maximization problem can again be solved using the Lagrangian method. The Lagrangian function has the form:

$$L\left(x_1, K, L, \lambda\right) = p_1 x_1 - p_K K - p_L L + \lambda\left(F_{x_1}(K, L) - x_1\right)$$

Taking the partial derivates results in the four first order conditions

$$\frac{\partial L}{\partial x_1} = p_1 - \lambda = 0 \tag{28.4}$$

$$\frac{\partial L}{\partial K} = -p_K + \lambda \frac{\partial F_{x_1}}{\partial K} = 0 \tag{28.5}$$

$$\frac{\partial L}{\partial L} = -p_L + \lambda \frac{\partial F_{x_1}}{\partial L} = 0 \tag{28.6}$$

$$\frac{\partial L}{\partial \lambda} = F_{x_1}(K, L) - x_1 = 0 \tag{28.7}$$

By solving (28.5) and (28.6) for λ, the equations can be set equal and through rearranging it follows that:

$$\frac{\frac{\partial F_{x_1}}{\partial K}}{\frac{\partial F_{x_1}}{\partial L}} = \frac{p_K}{p_L}$$

Such that the MRTS is equal to the relation of factor prices. Analogously, the maximization problem can be solved for firm 2 producing x_2. As both firms face the same factor prices, the MRTS are equal and production efficiency is fulfilled.

Finally, it needs to be shown that the quantities of goods produced align with the consumer preferences, i.e. product-mix-efficiency is fulfilled. Mathematically, the MRT_{x_1,x_2} is defined as $\frac{MC_1}{MC_2}$, the relation between the marginal costs of the production of the two goods. In a competitive market, firms maximize their profit at an output level where the price of the good equals the marginal costs of its production. Therefore, it holds that $\mathrm{MRT} = \frac{MC_1}{MC_2} = \frac{p_1}{p_2}$. Having shown above that the MRUS is equal to the relation of the prices of the goods, $\mathrm{MRT}_{x_1,x_2} = \mathrm{MRUS}_i$ and thus, product-mix-efficiency is fulfilled.

In a general market equilibrium, it holds that all markets are cleared, i.e. demand equals supply, household budgets are spent entirely, and all available resources are used in production. Thus, as all efficiency criteria are fulfilled simultaneously, the market equilibrium is a Pareto Optimum.

28.1.4 Variety of Efficient Allocations

Figures 28.1 and 28.2 show a general example for the optimality conditions of the allocation of resources and inputs in a market. In fact, there exist multiple indifference curves for consumers and isoquants for the firms producing the goods for which the optimality conditions hold. Thus, multiple Pareto optimal allocations of goods and inputs can exist in a market. Regarding the overall social welfare, one or the other allocation might be preferable, which can be achieved through redistribution of incomes as the second Theorem of Welfare economics states. This is further explained ▶ here.

28.2 Environmental Economics

28.2.1 Market Failures

In environmental economics, market failures are significant contributors to the inefficient allocation of resources, especially when it comes to environmental goods and services. This section explores the mechanisms of market failure, with a focus on externalities, public goods and common pool resources, while considering how these issues are addressed within the context of the bioeconomy. Understanding these concepts helps to analyse and propose sustainable economic practices that are in line with environmental objectives.

Market failure arises when the free market's allocation of goods and services is inefficient, meaning that resources are not distributed in a way that maximizes societal welfare. Ideally, market prices should reflect both the benefits and costs associated with production and consumption, leading to a Pareto-efficient outcome where no one can be made better off without making someone else worse off. However, in practice, certain conditions hinder this efficiency, particularly in environmental contexts (Stiglitz 2009).

Two primary sources of market failure are externalities and the non-market provision of public goods. In both instances, individual actors in the economy, producers or consumers, do not bear the full costs or reap the full benefits of their decisions. This leads to outcomes that are suboptimal for society.

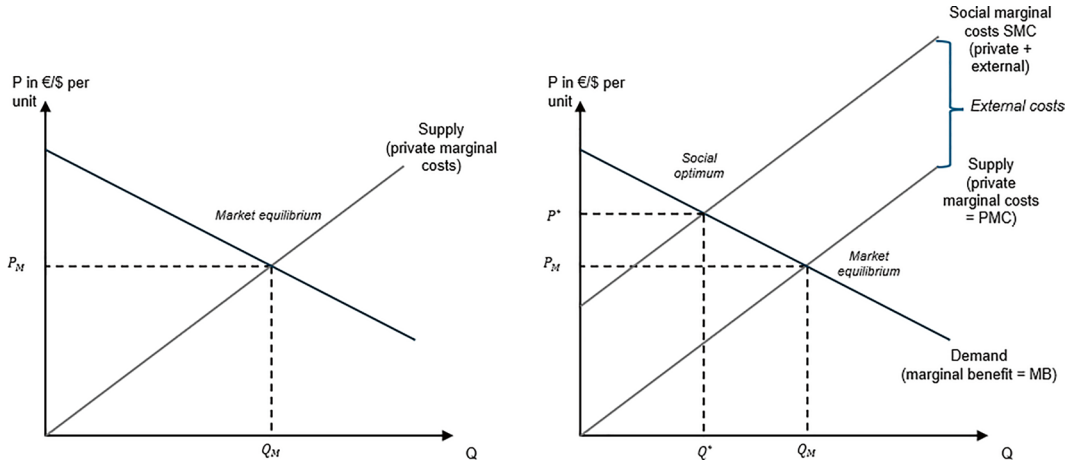


Fig. 28.4 Market in equilibrium (left) and social optimum including negative externalities (right). Source: Own illustration based on Harris and Roach (2018, pp. 44–46)

28

28.2.1.1 Externalities: Unseen Costs and Benefits

Externalities are a key source of market failure in environmental economics. An externality occurs when the actions of an individual or firm affect the welfare of others, but this impact is not reflected in market prices. Externalities can be either positive (benefits) or negative (costs), and their presence means that the market fails to account for the full social value or cost of goods and services (Salvatore 2003).

▪ Negative Externalities

Pollution is a classic example of a negative externality. When firms produce goods, they may release pollutants into the air or water, degrading the environment. These environmental damages impose costs on society, such as increased healthcare expenses for residents or harm to ecosystems, which the firm does not bear directly. Since these external costs are not factored into the price of the goods produced, firms lack a financial incentive to limit pollution, leading to overproduction relative to what is optimal for society.

In the left diagram of Fig. 28.4, the supply curve reflects only the producer's private marginal cost (PMC), which represents the cost of producing an additional unit of output from the firm's perspective. The market equilibrium is found at the intersection of the PMC (supply) and demand curves, resulting in a quantity QM and price PM where externalities are disregarded. In the diagram on the right, however, the social cost of production is incorporated by accounting for the negative externalities associated with pollution. Here, the supply curve reflects the social marginal cost (SMC), which is the sum of the private marginal cost and the external cost imposed on society. When these externalities are considered, the socially efficient equilibrium occurs at a higher price (P′) and a lower quantity (Q'), reducing the overconsumption and overproduction of goods with negative societal impacts (Harris and Roach 2018; Salvatore 2003).

For example, in the automotive industry, the private costs of manufacturing and operating vehicles exclude the environmental costs of air pollution and greenhouse gas emissions. As a result, cars are produced and consumed at levels exceeding the socially optimal quantity, which intensifies climate change and public health risks.

▪ Positive Externalities

Positive externalities arise when the actions of an individual or firm generate benefits for others that are not accounted for in market transactions. A notable example in environmental economics is afforestation, e.g. a landowner planting trees. While the landowner may gain

from increased timber yields or higher land value, society benefits as well through improved air quality, carbon sequestration and enhanced biodiversity. However, because the landowner is not compensated for these broader societal benefits, there is often underinvestment in activities like afforestation compared to the socially optimal level.

In both cases, whether externalities are positive or negative, the market outcome is inefficient because prices fail to reflect the full social costs or benefits of the activity. This underscores a central challenge in environmental economics and highlights the need for interventions to address these market failures (Harris and Roach 2018; Salvatore 2003).

28.2.1.2 Public Goods and Common-Pool Resources

Beyond externalities, another significant source of market failure is the supply of public goods and the management of common pool resources. These types of goods are defined by their non-excludability and non-rivalry (see ◘ Table 28.1), making them difficult to regulate through traditional market mechanisms.

▪ Public Goods

Public goods are both non-excludable and non-rival, meaning that no one can be excluded from their use, and one individual's consumption does not reduce availability for others. Examples include clean air and public parks. Because these goods are freely available to everyone, individuals have no incentive to pay for them, leading to underinvestment. This creates what is known as the free-rider problem, where people benefit from a good without contributing to its cost (Perman 2003; Salvatore 2003).

In the bioeconomy, public goods such as biodiversity and ecosystem services are crucial for the sustainability of biological resources. However, since these goods are not traded in markets and are not owned by anyone, there is little incentive for private entities to invest in their preservation. This can result in overuse or degradation, as seen in the depletion of natural habitats or loss of species diversity.

To address the market failures associated with public goods, governments often intervene by providing or protecting these goods through taxation and regulation. For instance, national parks and conservation areas are maintained using public funds, ensuring that they remain protected for future generations.

◘ Table 28.1 Types of goods. Source: Own Illustration based on Perman (2003, p. 126)

	Excludable	Non-excludable
Rival	Private good	Common-Pool resource
Non-Rivalrous	Club good	Public good

▪ Common Pool Resources

Common pool resources, such as fisheries, forests and groundwater, are rival but non-excludable. This means that while one person's use of the resource reduces its availability for others, it is difficult to restrict access to it. As a result, common pool resources are prone to overexploitation, leading to what is commonly referred to as the tragedy of the commons (Perman 2003; Salvatore 2003).

In the bioeconomy, many biological resources are common pool resources, and their sustainable management is essential to preserving ecosystem health. Without clear property rights or regulatory mechanisms, individuals are incentivized to maximize their use of the resource, even if it results in long-term depletion. A prominent example is overfishing in international waters, where individual fishers have no reason to limit their catch, potentially leading to the collapse of fish stocks (Perman 2003).

Addressing this so-called tragedy of the commons (Hardin 1968) requires collective action, either through the establishment of property rights or government intervention. Tools such as quotas, licenses, or tradable permits can regulate access and ensure sustainable use of these resources. For instance, fishing quotas can help prevent overfishing,

while carbon trading schemes limit total greenhouse gas emissions and allow firms to trade permits to achieve environmental goals efficiently.

The Importance of Property Rights

A fundamental issue in both externalities and the management of public goods and common pool resources is the absence of well-defined property rights. Property rights determine who controls resources and how they can be used. In cases where property rights are unclear or non-existent, as is often the case with environmental goods, markets fail to allocate resources efficiently. For many environmental goods, such as clean air or biodiversity, property rights are difficult to assign because these resources are shared by all and cannot be easily divided. Without property rights, individuals have no incentive to conserve or invest in the resource, leading to overuse and depletion (Salvatore 2003).

In the bioeconomy, establishing property rights for biological resources can help promote their sustainable use. For example, assigning property rights to forests or fisheries can give owners an incentive to manage these resources sustainably, as they can directly benefit from their conservation efforts. Similarly, tradable permits for carbon emissions create a market for pollution rights, incentivizing firms to reduce their emissions and invest in cleaner technologies.

Conclusion

Market failures are a fundamental concern in environmental economics, especially within the bioeconomy, where biological resources and ecosystems are essential to both production processes and societal well-being. Externalities, public goods and common pool resources are key sources of market failure, necessitating interventions to promote efficient and sustainable market outcomes. The following section examines policy instruments designed to address and correct these types of market failures.

28.2.2 Policy Instruments for Environmental Management

To correct the inefficiency caused by market failure, economists advocate for the internalization of external costs and benefits. Internalization means incorporating external effects into market prices so that consumers and producers face the true social costs and benefits of their decisions. This can be achieved through various policy instruments, which can be grouped into three broad categories: institutional approaches, command-and-control regulations and fiscal or quasi-market mechanisms (OECD 1999). This section explores these instruments, their mechanisms, and their suitability in different contexts, focusing on achieving cost-effective, ecologically efficient and socially equitable outcomes.

Types of Policy Instruments

To achieve efficient resource allocation and control externalities, policy instruments can be categorized into three main types:

1. *Institutional Approaches:*
   These aim to promote voluntary internalization of externalities by improving social responsibility or strengthening property rights. Such measures may include education, awareness campaigns or product labelling to influence consumer behaviour.
2. *Command-and-Control Instruments:*
   These involve direct regulations, such as emission limits, quotas or technology standards, mandating specific behaviours or outcomes. Governments use these instruments to impose restrictions or requirements to reduce pollution or manage resource use.
3. *Fiscal/Quasi-Market Instruments:*
   These create financial incentives through mechanisms like taxes, subsidies or tradeable permits, aligning private decision-making with social goals. These instruments are widely regarded as the most effective for addressing environmental externalities, particularly greenhouse gas emissions.

Each of these instruments has its strengths and limitations, depending on the environmental problem being addressed. Policymakers must evaluate their options based on criteria such as ecological efficiency, cost-effectiveness and equity, factors essential for designing effective policies.

28.2.2.1 Evaluating Policy Instruments

Each policy instrument has its advantages and limitations, and no single solution is ideal in all situations. Policymakers must take into account the specific environmental issue, economic context and available information when designing policies. Various criteria can be used to evaluate policy instruments, and in some cases, a combination of approaches may be necessary to achieve multiple objectives (Perman 2003). For example, Pigouvian taxes could be combined with subsidies for green technologies, or command-and-control measures could be complemented by market-based instruments to create a more flexible and dynamic regulatory framework.

Criteria for Evaluating Policy Instruments

The selection of an appropriate policy instrument depends on how well it meets several key criteria:

- Ecological Efficiency: This refers to the instrument's ability to achieve a given environmental target, such as reducing emissions to a socially optimal level. Ideally, this level balances the marginal cost of pollution reduction with the marginal damage caused by pollution.
- Cost-Effectiveness: The instrument should achieve its target at the lowest possible cost, aligning with the "least cost theorem" of pollution control, which states that the marginal cost of pollution reduction (MCR) should be equalized across all firms.
- Dynamic Efficiency: Instruments should create ongoing incentives for technological innovation, reducing pollution over time.
- Equity: Policy instruments can have different distributional impacts, meaning they may affect some groups or regions more than others. Equity considerations are especially important in the bioeconomy, where resource use can influence livelihoods.
- Flexibility: Policies should be adaptable to new information, allowing for adjustments as conditions evolve.
- Information Requirements: Some instruments need significant data about firms' pollution costs, or the environmental damage caused by pollution. High information requirements can be a barrier to the effective implementation of certain policies.

28.2.2.2 Institutional Approaches

Institutional approaches to environmental policy aim to foster voluntary behaviour change or improve the management of property rights. By encouraging greater social responsibility or altering societal norms, these approaches seek to reduce environmental harm without the need for direct intervention (Harris and Roach 2018). An example of an institutional approach is product labelling, such as energy efficiency labels on appliances. By providing consumers with clear information, labels allow them to make informed choices that align with environmental goals.

However, while institutional approaches are relatively low-cost and flexible, they are often not as effective in achieving large-scale pollution reduction. They typically do not directly influence producers, and their impact depends heavily on individual behaviour changes, which may be slow to materialize.

28.2.2.3 Command-and-Control Instruments

Command-and-control instruments are among the most traditional forms of environmental regulation. These regulations can take several forms, including:

- Technology Standards: Governments may mandate the use of specific technologies to reduce emissions, such as catalytic converters in cars. These standards are effective in ensuring compliance but often lack flexibility and may not encourage ongoing innovation. Firms are required to use the

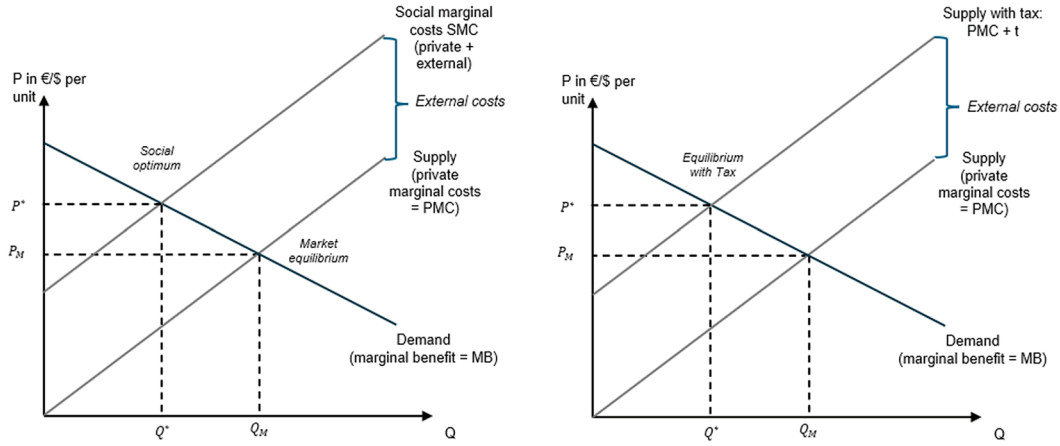


Fig. 28.5 Market with negative externalities (left) and with Pigouvian tax (right). Source: Own illustration based on Harris and Roach (2018, pp.46–48)

mandated technology even if cheaper or more efficient alternatives exist.

- Emission Limits and Quotas: These set a maximum allowable level of pollution for firms or industries. Non-compliance is typically penalized, ensuring firms adhere to the set limits. However, the rigidity of such policies can lead to inefficiencies. Firms with higher pollution abatement costs may struggle to meet these limits, while others with lower costs may be capable of reducing emissions more cheaply.

While command-and-control policies are often ecologically effective, they are not cost-effective or dynamically efficient. These policies do not equalize the marginal cost of pollution reduction across all firms, leading to situations where some firms face higher costs than others. Additionally, such instruments provide little incentive for firms to innovate or exceed regulatory standards.

28.2.2.4 Fiscal/Quasi-Market Instruments

Fiscal and quasi-market instruments are increasingly favoured in environmental policy for their ability to internalize externalities and create market-based incentives for pollution reduction. Two prominent examples are Pigouvian taxes and marketable permits.

Pigouvian Taxes

A Pigouvian tax is a per-unit tax on a pollutant that reflects the external damage caused by that pollutant. By imposing this tax, the government corrects the market failure associated with negative externalities, ensuring that the social cost of pollution is reflected in market prices (Harris and Roach 2018).

Consider a firm whose production generates environmental harm through emissions. In the left graph of Fig. 28.5, the private marginal cost (PMC) curve reflects only the firm's internal production costs. However, to reach a socially optimal outcome at price P', the external cost of environmental damage must be internalized to represent the true social cost of production (see ▶ Sect. 28.2.1.1).

This internalization can be achieved by applying a Pigouvian tax on the firm's emissions. By adding the per-unit tax (t) to the private marginal cost, the firm's supply curve shifts upward, aligning the private marginal cost with the social marginal cost (SMC). Consequently, the new market equilibrium occurs at a higher price (P′) and a lower quantity (Q'), closer to the socially optimal outcome (Sandmo 2008). This approach embodies the polluter pays principle (OECD 2008), asserting that those responsible for environmental harm should bear the cost of

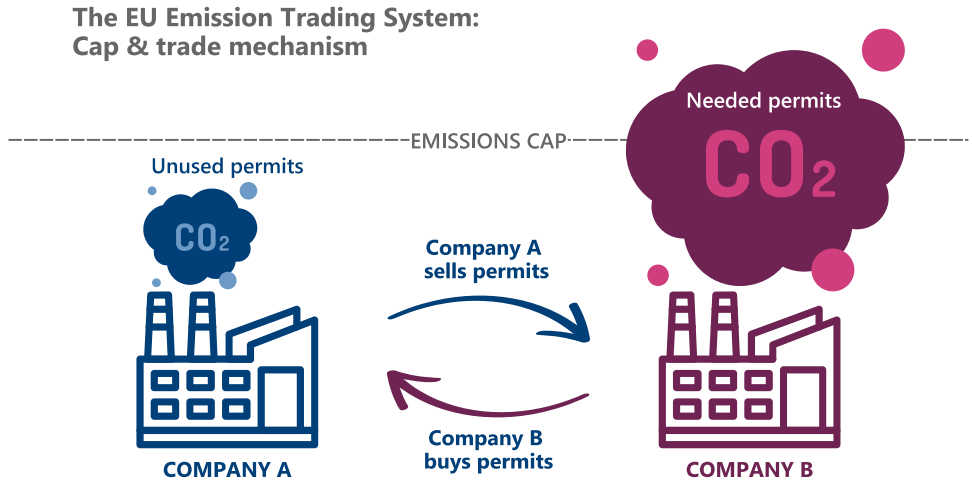


Fig. 28.6 The EU Emissions Trading System. Source: Adapted from Climate Policy Info Hub (n.d.)

mitigation. By charging polluters for the external damage they inflict, Pigouvian taxes not only correct market prices but also incentivize firms to reduce their environmental impact. In the bioeconomy, such taxes could be applied to activities that degrade ecosystems, encouraging more sustainable practices.

Pigouvian taxes are both ecological and cost-efficient, as they provide continuous incentives for firms to innovate and reduce pollution. However, they can face political resistance, particularly if they disproportionately affect low-income households or regions that rely heavily on polluting industries.

Marketable Permits (Cap-and-Trade)

Marketable permits, or cap-and-trade systems, establish a limit on total emissions and allocate or auction permits to polluters. Firms are allowed to trade these permits, creating a market for the right to pollute. Firms with higher costs of pollution avoidance can purchase permits from those that can reduce pollution more cheaply, ensuring that emissions are reduced at the lowest overall cost (Harris and Roach 2018).

A well-designed cap-and-trade system achieves similar ecological and cost efficiency as a Pigouvian tax but with added flexibility. Additionally, the system creates a price signal for pollution, which encourages firms to invest in cleaner technologies over time. The European Union Emissions Trading System (EU ETS), launched in 2005, is the largest cap-and-trade system globally (see Fig. 28.6). By 2023, emissions from sectors covered by the EU ETS had decreased by 47% compared to 2005 level, underscoring its effectiveness in reducing emissions in the power and industry sectors (European Commission 2024).

28.2.3 Limitations of Classical Approaches

While emission taxes and cap-and-trade systems are effective tools for reducing emissions, they come with inherent limitations. Incomplete behavioural change is a significant issue, as not all individuals or businesses respond to price signals by adjusting their behaviour enough to meet emission reduction targets. Some may simply absorb the additional costs without altering their consumption or production patterns. Additionally, technological constraints in some sectors limit the availability of low-carbon alternatives, making it difficult to reduce emissions solely through market mechanisms. Finally, equity concerns arise, as emission taxes can disproportionately impact lower-income households, raising questions of fairness. Complementary policies are necessary to

address these distributional effects (Burtraw et al. 2008).

Conclusion

In summary, the choice of environmental policy instruments involves balancing ecological efficiency, cost-effectiveness, equity and other criteria. Institutional approaches, command-and-control measures and fiscal/quasi-market instruments each offer distinct advantages and limitations. The key challenge for policymakers is to select the right mix of instruments to correct market failures and promote sustainable resource use in the bioeconomy. By understanding the trade-offs involved, effective environmental policies that contribute to both economic and environmental goals can be designed.

28.3 Mitigation and Adaptation in Climate Economics: The Role of the Bioeconomy

Climate change presents major challenges to economies, ecosystems and societies globally. Mitigating these challenges requires a multifaceted approach that combines reducing greenhouse gas (GHG) emissions—mitigation—and adjusting systems to minimize the harm from climate impacts—adaptation. Traditional climate economics has focused on policy instruments like emission taxes and cap-and-trade systems to internalize the external costs of GHG emissions. However, these classical approaches have limitations. Not all emissions can be eliminated through behavioural changes, and certain emissions are unavoidable due to essential activities like food production. For example, livestock farming releases methane—a potent greenhouse gas—through enteric fermentation in the digestive systems of ruminant animals like cows and sheep. Rice cultivation is another example; flooded paddy fields create anaerobic conditions that lead to methane production. Additionally, the use of nitrogen-based fertilizers in agriculture results in nitrous oxide emissions. A sustainable bioeconomy utilizes renewable biological resources and offers additional pathways to further reduce or remove emissions. This chapter explores the economic rationale behind mitigation and adaptation, examines classical climate policy approaches, highlights their limitations, and makes a case for integrating bioeconomic strategies into climate policy.

28.3.1 Economic Rationale for Mitigation and Adaptation

Climate change characterizes a market failure arising from negative externalities. GHG emissions from industrial activities, transportation and other sources impose costs on society—such as health issues, environmental degradation and property damage—that are not reflected in the market prices of goods and services whose production causes emissions (Stern 2007). This discrepancy leads to overproduction of emissions, as producers and consumers do not bear the full social costs of their actions.

Mitigation policies aim to correct this market failure by internalizing the external costs of emissions. By doing so, they align private incentives with social welfare, encouraging reductions in GHG emissions. Adaptation, on the other hand, addresses the consequences of climate change that are already occurring or are inevitable due to past and present emissions. From an economic standpoint, adaptation reduces the damages associated with climate impacts, thereby lowering the overall costs to society (IPCC 2014). Both mitigation and adaptation are complementary components of a comprehensive climate policy. While classic mitigation approaches have been explained in detail in the previous section, the following section highlights the role of the bioeconomy in mitigation and adaptation.

28.3.2 The Bioeconomy as a Complementary Approach

The bioeconomy offers promising solutions to address the shortcomings of classical climate policies. By utilizing renewable biological resources sustainably, the bioeconomy can contribute to both mitigation and adaptation efforts, further reducing or removing emissions that are difficult to eliminate through behavioural changes alone.

28.3.2.1 Mitigation Through the Bioeconomy

Bioenergy, derived from biomass such as agricultural residues, forestry by-products and energy-dedicated crops, offers a sustainable alternative to fossil fuels in energy production. When managed responsibly, bioenergy can lead to a significant reduction in net greenhouse gas (GHG) emissions. Biofuels like ethanol and biodiesel, for example, are increasingly used in transportation to decrease dependency on petroleum-based fuels. A prominent example is Brazil's use of sugarcane ethanol, which has played a vital role in reducing GHG emissions from its transportation sector while bolstering energy independence (Goldemberg et al. 2008). ► Section 28.4 will shed light on the advantages and disadvantages of biofuels with a view to EU biofuel policies.

In addition to providing cleaner energy, bio-based processes contribute to carbon sequestration—capturing and storing carbon dioxide from the atmosphere. Techniques like afforestation (planting new forests) and reforestation (restoring depleted forests) are effective ways to expand carbon sinks. Soils are also critical in this process, as practices such as conservation tillage and cover cropping help enhance soil organic matter, allowing soils to sequester substantial amounts of carbon (Lal 2004). Emerging technologies like Bioenergy with Carbon Capture and Storage (BECCS) hold promise for achieving negative emissions. BECCS combines bioenergy production with carbon capture, storing the CO_2 emitted during biomass energy production underground, potentially removing carbon from the atmosphere. While BECCS offers significant potential for both energy production and carbon removal, it faces challenges in terms of cost, technology and sustainability (IPCC 2018).

28.3.2.2 Adaptation Through the Bioeconomy

The bioeconomy offers a strategic approach to adaptation by fostering climate-resilient agricultural systems and promoting sustainable practices. By *developing crop varieties that are tolerant to heat, drought and pests*, agricultural productivity can be maintained or enhanced under changing climate conditions (Ortiz et al. 2008). Both biotechnology and traditional breeding techniques play crucial roles in this. *Urban agriculture* (see ► Chap. 7) also contributes by enhancing food security and resilience in urban areas through methods like rooftop gardens, vertical farming and community gardens. This not only reduces the carbon footprint from food transportation but also improves local food availability, supporting both mitigation and adaptation efforts (Despommier 2010). In addition, *adopting sustainable agricultural practices* such as conservation agriculture, agroforestry and organic farming further strengthens the resilience of agricultural systems (see ► Sect. 7.11). These methods improve soil health, increase biodiversity and enhance water retention, making crops more resistant to climate variability and extreme weather (Pretty et al. 2011). *Agroforestry*, which integrates trees into agricultural landscapes, not only sequesters carbon but also provides habitat for biodiversity, improves soil fertility and diversifies farmers' income sources (Nair 2007). Moreover, the *restoration and conservation of ecosystems* like wetlands, mangroves and forests offer natural defences against climate impacts. These ecosystems act as buffers against storms, floods and erosion while supporting biodiversity and providing livelihoods

for local communities (Munang et al. 2013) (see Excursus 6.1). An exemplary case is the ▶ Netherlands' Delta Programme, which focuses on sustainable water management and ecosystem restoration to protect the country from flooding while promoting biodiversity and recreational opportunities.

28.3.3 Integrating Bioeconomic Strategies into Climate Policy

To fully realize the potential of the bioeconomy in mitigating and adapting to climate change, it is essential to integrate bioeconomic strategies into climate policy frameworks.

▪ Policy Instruments Supporting the Bioeconomy

Governments play a crucial role in advancing the bioeconomy through a variety of policy instruments that promote the use of renewable resources and sustainable practices. One such instrument is the use of *subsidies and financial incentives*, where governments provide financial support, such as subsidies, tax credits and grants, to encourage the adoption of bioenergy, bio-based materials and sustainable agricultural practices. These incentives help lower the financial barriers to adopting new technologies and foster investment in the bioeconomy. A successful example of this approach is Germany's Renewable Energy Sources Act (EEG), which offers feed-in tariffs and other support mechanisms for renewable energy producers, including those using biomass. As a result, there has been a significant increase in the share of renewables in the country's energy mix. The proportion of renewable power has increased from 5.4% in 1999 to over 40.3% in 2017 due to the impact of the ▶ EEG. In addition, Sect. 28.4 will discuss EU biofuels policies.

Another key policy tool is *research and development (R&D)*. By investing in R&D, governments can accelerate the advancement of bio-based technologies and practices. Public funding and support for innovation are essential in overcoming technological hurdles and reducing costs, thereby making the bioeconomy more accessible and efficient. In addition to financial and research support, *regulations and standards* are crucial for ensuring the sustainability of bioeconomic activities. The implementation of sustainability criteria and certification schemes helps guarantee that bioeconomic efforts deliver real environmental benefits without causing unintended harm, such as deforestation or biodiversity loss (see ▶ Sect. 31.2). As discussed in the next section, the European Union's Renewable Energy Directive, for instance, includes measures to prevent negative impacts from biofuel production, ensuring that the shift towards renewable energy does not come at the expense of ecological balance.

28.3.4 Addressing Challenges

While the bioeconomy holds significant promise, it also presents challenges that need to be tackled through thoughtful policy design. *Sustainability concerns* arise when expanding bio-based production without proper management, potentially leading to deforestation, water scarcity and biodiversity loss. Policies must enforce sustainable land management practices to prevent these outcomes (Searchinger et al. 2008). *Land use competition* is another issue, as balancing land for food, feed, fibre and fuel requires integrated planning (see ▶ Sect. 28.4.). Policies should promote efficient land use and address potential trade-offs. *Technological and economic barriers* also impede the adoption of bioeconomic solutions due to high initial costs and technical challenges. Supportive policies, including subsidies and research funding, are essential to overcoming these hurdles. Additionally, *food security and equity* must be safeguarded, ensuring that the expansion of bioenergy crops does not compromise food availability or disproportionately affect vulnerable populations. Policies should ensure that bioeconomic development is both inclusive and equitable (FAO 2018).

Conclusion

Classical climate policies like emission taxes and cap-and-trade systems are essential tools for reducing GHG emissions by internalizing external costs and incentivizing behavioural changes. However, their limitations necessitate additional approaches to achieve comprehensive emission reductions and address unavoidable emissions.

The bioeconomy offers a complementary pathway by providing sustainable, bio-based solutions that can further reduce or remove emissions. By integrating bioeconomic strategies into climate policy, we can enhance mitigation and adaptation efforts, promote sustainable economic development and address some of the challenges inherent in classical approaches.

Effective integration requires supportive policies that incentivize sustainable practices, invest in research and development and address potential trade-offs and equity concerns. Policymakers must adopt a holistic perspective that considers environmental, economic and social dimensions to fully leverage the bioeconomy's potential in transitioning to a low-carbon, climate-resilient future. The following section will highlight the challenges of inclusive policy-making within the bioeconomy and the role of economic markets.

28.4 The EU Renewable Energy Directive (RED): Biofuel Policies for Climate Change Mitigation and Indirect Land Use Change

28.4.1 Renewable Energy Policy in the European Union

The European Union has established comprehensive policies to promote the production and use of renewable energy, targeting a shift away from fossil fuels and toward sustainable energy sources. This strategy aims to address both environmental and energy security concerns while fostering a greener, more sustainable economy. Central to these policies is the ► Renewable Energy Directive (RED), which has undergone several revisions to adapt to evolving technologies, environmental challenges and social considerations.

28.4.1.1 Renewable Energy Directives: RED I, RED II and the 2023 Amendment

The first Renewable Energy Directive (RED I) was introduced in 2009 with targets extending to 2020. This directive aimed to ensure that renewable energy sources met a growing share of the EU's overall energy demand. It set binding goals for member states, including achieving a certain percentage of renewable energy across sectors such as electricity, heating and cooling, with a specific focus on transportation.

In 2018, RED II was adopted, setting a new framework for renewable energy targets through 2030. This directive introduced more ambitious targets, emphasizing the need for renewable energy to meet at least 32% of the EU's total energy demand by 2030. It also strengthened sustainability criteria. An amendment in 2023 further tightened these goals, aligning the directive with the EU's Green Deal objectives, which aim to achieve net-zero emissions by 2050. For further information, see ► Renewable energy targets.

28.4.1.2 Special Targets and Policies for the Transport Sector

The EU's renewable energy policy includes specific mandates for the transport sector, a significant source of carbon emissions. The directive establishes mandated purchase quotas for biofuels, requiring that a set percentage of transport fuels be derived from renewable sources, particularly biofuels (see ► Sect. 28.4). This quota functions similarly to a subsidy, encouraging the adoption of biofuels by setting legal requirements for their use. However, the push for biofuels raises potential trade-offs that the EU tries to address with several sustainability criteria:

- *Environmental sustainability*: Biofuels must meet rigorous criteria to qualify as renewable. To limit their environmental impact, the EU mandates that biofuels used in transportation meet standards for emissions reduction and avoid causing significant land-use change, which can disrupt ecosystems and release additional carbon stored in soil. To this end, the policies address land-use changes, water usage and biodiversity impacts.
- *Social sustainability*: There is concern over the use of food crops for biofuel production, as this could impact food availability and prices. RED II and subsequent policies emphasize that biofuels should be produced sustainably without compromising food security, especially in vulnerable regions.

28.4.1.3 Sustainability Criteria for Biofuels in RED II

The EU's Renewable Energy Directive II (RED II) includes specific sustainability criteria for biofuels used in the transport sector. These criteria are designed to ensure that biofuels provide real environmental benefits and can be counted toward the EU's 14% renewable energy target for transport. The key sustainability criteria under RED II address greenhouse gas (GHG) emissions and land use concerns.

1. Minimum Greenhouse Gas (GHG) Emission Savings

One of the core sustainability requirements is that biofuels must achieve significant GHG emission reductions compared to traditional fossil fuels. RED II sets minimum thresholds for these savings to ensure that biofuels make a meaningful contribution to reducing overall emissions.

- New Biofuel Production Facilities: Biofuels produced in facilities built after RED II came into effect must achieve at least a 65% reduction in GHG emissions relative to fossil fuels.
- Existing Biofuel Facilities: Biofuels from facilities already in operation prior to RED II are required to meet a minimum of 50% GHG savings.

2. Land Use and Potential Land Use Change

RED II also addresses the environmental impacts related to land use, particularly the risk of indirect land use change (ILUC). "ILUC-emissions occur when grassland and forest are converted to cropland somewhere on the globe to meet the demand for commodities displaced by the production of biofuel" (Plevin et al. 2020). This land conversion can result in substantial carbon emissions, offsetting the climate benefits of biofuels.

To minimize these risks, RED II includes criteria for sustainable land use:

- No Conversion of High-Biodiversity Areas: Biofuel crops must not be sourced from lands with high biodiversity, such as primary forests, nature reserves or grasslands rich in biodiversity. This requirement protects vital ecosystems and prevents biofuel production from causing deforestation or ecosystem degradation.
- Classification of High-ILUC-Risk Biofuels: RED II classifies certain biofuel feedstocks as having a high ILUC risk if they are linked to significant land-use change. This classification is based on whether their production is likely to lead to increased demand for agricultural land, causing forests, wetlands or other high-carbon stock areas to be converted into farmland. So far, only palm oil has been classified as a high ILUC-risk feedstock because of its strong association with deforestation and land-use change in tropical regions. The directive sets a timeline for phasing out high-ILUC-risk biofuels. From 2023 to 2030, the EU plans to gradually reduce the use of biofuels derived from high ILUC-risk crops, with the goal of completely eliminating them from the renewable energy target for transport by 2030.

While these criteria are in principle commendable to improve sustainability of biofuels, their practical policy implications demonstrate the complexity of the role of policies and biofuels through market interactions as highlighted in the next section.

28.4.2 The Indirect Land Use Change (ILUC) Controversy and Biofuels

As mentioned above, ILUC refers to the indirect consequences that arise when biofuel production increases demand for agricultural land, potentially leading to the conversion of forests, grasslands or other non-agricultural lands into cropland. A study by Searchinger et al. (2008) highlighted this issue, suggesting that biofuels could increase rather than reduce GHG emissions due to ILUC effects. However, ILUC is fundamentally a global market effect caused by the increasing demand for biofuels. When crops like corn, soy or sugarcane are used as biofuel feedstocks, the demand for these crops rises. This increased demand can drive up crop prices, making agricultural production more profitable. Consequently, farmers and agricultural businesses have economic incentives to expand cropland to meet the higher demand. This expansion often involves converting land that was previously unused or used for other purposes—such as forests, wetlands, or grasslands—into agricultural land.

28.4.2.1 Challenges in Isolating ILUC Effects

One of the main challenges in addressing ILUC is that it is difficult to isolate the impact of biofuel policies on land use from other global and local factors. Various market effects beyond biofuel demand influence land use changes, including:

- Consumer preferences: Shifts in consumer demand for different food products can affect crop prices and land use patterns.
- Geopolitical shocks: Events such as trade disputes, embargoes, or regional conflicts can disrupt agricultural markets and influence land use decisions globally.
- Agricultural subsidies: Government subsidies for certain crops can impact land use by making specific types of agriculture more profitable.

These factors make it complex to attribute land use changes directly to biofuel policies alone, as land use decisions are influenced by an interconnected web of economic and political conditions.

28.4.2.2 Methods to Identify and Measure ILUC Due to Biofuel Policies

Given these complexities, researchers and policymakers rely on scenario analysis and economic simulation models to estimate the potential ILUC impacts of biofuel policies. Scenario analysis (see ► Sect. 42.3) involves creating hypothetical situations based on different policy choices and observing their projected outcomes on land use. Economic simulation models attempt to isolate the effects of biofuel demand on land use by accounting for other variables in the global agricultural market. More on models can be found in ► Chap. 42.

However, these methods have limitations. The results depend heavily on assumptions—such as estimates of how much unused land is available for conversion, the types of crops grown and the efficiency of agricultural practices. These assumptions introduce uncertainties into ILUC predictions, making it difficult to produce definitive conclusions about the extent of ILUC effects due to biofuel policies. As a result, ILUC modelling can highlight potential risks but cannot provide a precise measurement of actual land use changes attributable solely to biofuel demand.

28.4.2.3 The RED II Ban on Palm Oil and the ILUC Controversy

As described above, the RED II has classified palm oil as a crop with a high ILUC risk due to the environmental concerns associated with

its production. As a result, RED II mandates that palm oil-based biodiesel be gradually phased out and ultimately banned from EU biodiesel production from 2023 until 2030. However, the decision to single out palm oil has sparked international controversy and raised questions about both trade implications and the overall effectiveness of the EU's renewable energy strategy.

The EU's palm oil restrictions have faced strong opposition from major palm oil-producing countries like Malaysia and Indonesia. These countries argue that the policy serves as a non-tariff barrier to trade designed to protect European biodiesel and oilseed producers (such as those producing rapeseed and sunflower oil) rather than addressing environmental concerns. They contend that this ban unfairly targets palm oil while allowing other crops, which may also have environmental drawbacks, to continue contributing to the EU's biodiesel targets.

For countries like Indonesia and Malaysia, palm oil is a critical economic resource, and restrictions on its use in the EU could have significant economic impacts. These countries argue that the EU's policy is selective and does not consider the full environmental impact of other biofuel feedstocks.

The Sustainability Paradox: Certification and Incentives for Sustainable Palm Oil

An important aspect of the EU's approach to palm oil is that palm oil used in EU biodiesel production must be certified to ensure that it meets certain sustainability standards (see ► Sect. 31.2). Certified palm oil is produced under the above-described sustainability criteria, including sustainable land management practices that minimize deforestation and habitat destruction.

However, if the EU completely phases out palm oil from its biodiesel market, this may unintentionally remove incentives for producers to invest in sustainable practices. Without access to the European market, palm oil producers may see less reason to pursue certification, potentially leading to even less sustainable practices as they seek markets with lower environmental standards. This outcome could undermine the very environmental goals the EU intends to achieve, as unsustainable palm oil production might increase in other markets without EU oversight and certification requirements.

Broader Concerns: Palm Oil, Other Problematic Crops and DLUC

While palm oil is undoubtedly associated with significant ILUC risks, focusing solely on palm oil may overlook the broader issue of Direct Land Use Change (DLUC), which occurs when forests, wetlands or other high-carbon lands are directly converted into agricultural use for any crop. DLUC can result in high emissions, regardless of the crop involved, which means that other biofuel feedstocks could also contribute to significant environmental degradation if not managed sustainably. By concentrating on palm oil alone, there is a risk of ignoring other biofuel crops with similar or even higher environmental impacts. For instance, soy, corn and rapeseed are all used in biofuel production and can also lead to DLUC and ILUC issues if not carefully managed. A comprehensive sustainability strategy would address these issues across all biofuel feedstocks, not just palm oil.

A recent study by Heimann et al. (2024) uses a computable general equilibrium (CGE) model (see ► Sect. 42.2) to analyse the impact of phasing out palm oil-based biodiesel, and additionally soy oil-based biodiesel, in the EU. The findings show that removing palm oil from EU biodiesel has a small effect on overall palm oil production and land use in tropical regions. However, phasing out soy oil has a stronger impact, reducing global soy production and cropland use in soy-producing regions. Both policies result in increased oilseed production within the EU, benefiting European farmers but reducing incomes for farmers in Malaysia and Indonesia. Additionally, EU firms and consumers face higher costs. The study highlights that single-product regulations, like the EU's focus on palm oil, are not enough for effective environmental protection. Broader, binding sustainability standards and certification for all vegetable oils across industries, along with better forest protection, are necessary.

To conclude, while biofuels are contributing to climate change mitigation through the replacement of fossil fuels, they can evoke several environmental trade-offs as explained in this chapter. Policies to avoid these trade-offs are often well meant but at the same time often short-sighted as they do not consider complex market effects. Therefore, the economic dimension of the bioeconomy is essential to capture these trade-offs and improve policy-making in the bioeconomy.

Questions

1. What is a pareto-efficient allocation? Is an efficient allocation a fair allocation? Why or why not?
2. What is an externality? Explain why this can be problematic with a view to pareto efficiency.
3. How can we internalize externalities?
4. What are the different types of environmental policy instruments?
5. What is indirect land use change?
6. What is the role of the Bioeconomy for climate change mitigation?

Answers

1. A Pareto-efficient allocation is one in which resources are allocated so that no one can be made better off without making someone else worse off. This type of allocation maximizes overall efficiency but does not necessarily address fairness or equity. An efficient allocation is not always a fair allocation because it only considers whether resources are fully utilized, not whether the distribution is equitable. For instance, a Pareto-efficient outcome could result in significant inequality, benefiting some individuals more than others without redistributing to ensure fairness. It often requires redistribution by governments to ensure equitable allocations.
2. An externality is a cost or benefit of an economic activity that affects the welfare of other economic agents. Externalities can be either negative (e.g. pollution affecting nearby residents) or positive (e.g. a well-maintained garden benefiting neighbours).

   Externalities are problematic for Pareto efficiency because they lead to market failures, where the full costs or benefits of a transaction are not reflected in the market price. In the case of negative externalities, for example, a firm might produce more pollution than is socially optimal because it does not bear the full costs, reducing overall welfare. This misallocation of resources prevents a Pareto-efficient outcome, as it is possible to make some individuals better off (e.g. by reducing pollution) without making others worse off, thus improving overall societal welfare.
3. Externalities can be internalized by adjusting incentives so that the agents causing the externalities bear the full social costs or benefits of their actions. Common methods include:
   (a) Taxes and Subsidies: Imposing a tax on negative externalities (e.g. a carbon tax on pollution) or providing subsidies for positive externalities (e.g. subsidies for renewable energy) aligns private costs or benefits with social ones.
   (b) Regulation: Setting legal limits or standards (e.g. emission caps) can directly reduce harmful externalities.
   (c) Tradable Permits: In systems like cap-and-trade for emissions, firms are allocated or can purchase permits to pollute, creating a financial incentive to reduce pollution.
4. The different types of environmental policy instruments are**:**
   (a) Institutional Approaches: These aim to promote voluntary internalization of externalities by improving social responsibility or strengthening property rights. Such measures may include education, awareness campaigns, or product labelling to influence consumer behaviour.
   (b) Command-and-Control Instruments: These involve direct regulations, such as emission limits,

quotas or technology standards, mandating specific behaviours or outcomes. Governments use these instruments to impose restrictions or requirements to reduce pollution or manage resource use.

(c) Fiscal/Quasi-Market Instruments: These create financial incentives through mechanisms like taxes, subsidies or tradeable permits, aligning private decision-making with social goals. These instruments are widely regarded as the most effective for addressing environmental externalities, particularly greenhouse gas emissions.

5. ILUC refers to the indirect consequences that arise when biofuel production increases demand for agricultural land, potentially leading to the conversion of forests, grasslands, or other non-agricultural lands into cropland. "ILUC-emissions occur when grassland and forest are converted to cropland somewhere on the globe to meet the demand for commodities displaced by the production of biofuel" (Plevin et al. 2020).
6. The bioeconomy plays a significant role in climate change mitigation by promoting the use of renewable biological resources and sustainable processes to replace fossil-based products and energy. By utilizing biomass for energy, materials and chemicals, the bioeconomy can reduce greenhouse gas emissions, sequester carbon and decrease dependency on fossil fuels. Additionally, bio-based products and processes—such as biofuels, bioplastics and sustainable agriculture—often have a lower carbon footprint and can help in developing carbon-neutral or even carbon-negative solutions.

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Stakeholders of the Bioeconomy

The transition to a sustainable economy requires sustainability-conscious producers and consumers to steer economic activities through their businesses, capabilities, targeted preferences and choices. This change needs to be guided by supporting policies. Research and education play an important role in developing innovations, educating the workforce for the bioeconomy and supporting the necessary interactions between the different actors in the bioeconomy. This part of the book, therefore, focuses on the roles and contributions of relevant stakeholders, who drive the transition to a sustainable bioeconomy, including politicians, farmers, entrepreneurs, consumers and researchers.

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Governance of the Bioeconomy

Regina Birner



Fig. 29.0 Governance of the Bioeconomy. (© Universität Hohenheim, Uta Rometsch) (▶ https://doi.org/10.1007/000-hva)

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This chapter discusses the governance of the bioeconomy. The first section introduces the concept of governance. The second section introduces the organisations of the public, private, and third sectors that play a role in the bioeconomy and discusses their interaction. The subject of the third section is the process of designing bioeconomy strategies. The fourth section deals with bioeconomy strategies as an important instrument of biodiversity governance. A competitiveness framework is used to classify different elements of the bioeconomy strategies. The final section discusses the governance challenges that the bioeconomy is confronted with.

Learning Objectives

After reading this chapter, you will…

- …be able to explain the concept of governance (see ► Sect. 29.1).
- …be able to identify the key stakeholders of the bioeconomy and understand their interactions (see ► Sect. 29.2).
- …be able to assess the role of bioeconomy strategies as governance instruments and to identify their main components (see ► Sects. 29.3 and 29.4).
- …be able to describe key challenges of bioeconomy governance (see ► Sect. 29.5).

29.1 The Concept of Governance

Etymologically, the term governance can be traced back to the Greek verb *kubernân*, which means 'to pilot' or 'to steer' and to the Latin word *gubernare*, which has a similar meaning (Kjaer 2004, p 2). There are many different definitions of governance, which evolved over time. In the political sciences, the term was initially used to refer to the act of governing, that is exercising authority by a government. Over time, the concept became broader to include the wide range of non-state actors, such as civil society organisations, and their networks, which are involved in the management of public affairs. International organisations, such as the World Bank and the United Nations, increasingly came to use the concept in a normative sense, referring to "good governance" and emphasising aspects such as legitimacy, transparency and accountability (Kjaer 2004, p 2–4). In economics, the term has been used to refer to the institutional structures in which economic activities, including the management of natural resources, are carried out. Examples of this use of the term are Williamson's (2005) paper on "Economics of Governance" and Ostrom's (1990) book on "Governing the Commons".

The concept of governance has also been applied to the bioeconomy. There is a growing literature that deals with "governance of the bioeconomy". Some examples that illustrate this literature include the following: Early studies, e.g. the one by Bailis and Baka (2011), focused on the governance of sub-fields of the bioeconomy, such as biofuel governance. Over time, studies on bioeconomy governance became more comprehensive. Under the title *Governance of the Bioeconomy*, Dietz et al. (2018) conduct a global comparison of national bioeconomic strategies. In a paper entitled *Good Governance in the Bioeconomy*, Devaney et al. (2017) analyse how principles of good governance, such as accountability and participation, are applied in the European Union. Böcher et al. (2020, p 4) review the literature on *Bioeconomy Politics and Governance* from a political science perspective and identify a set of research gaps that would need to be addressed to "fully understand underlying political interests and power relations of bioeconomy politics". To mention another example, Bößner et al. (2021) examine international institutions and their role in *Governing the bioeconomy*.

Taking the emerging literature on bioeconomy governance into account, the term *bioeconomy governance* is used here to refer to actors, institutions and processes that are relevant for 'steering' the development of the bioeconomy. Bioeconomy strategies are seen as a major governance instrument, or 'steering instrument' for bioeconomy development. The term *governance challenges* refers to the

obstacles that actors face in the processes of designing and implementing bioeconomy strategies.

The chapter is organised as follows. ▶ Section 29.2 presents a framework to identify the organisations that are relevant for the bioeconomy and to understand their interactions. ▶ Section 29.3 shows how the different actors can be involved in the development of bioeconomy strategies. In ▶ Sect. 29.4, a framework for classifying the elements of bioeconomy strategies is outlined. ▶ Section 29.5 describes major challenges of governing the bioeconomy.

29

29.2 Organisations Involved in the Bioeconomy and Their Interactions

29.2.1 Overview

Figure 29.1 displays a conceptual framework that can be used to identify the organisations involved in the bioeconomy and their interactions. The framework distinguishes between three different types of organisations: organisations of the private sector, organisations of the public sector and civil society organisations, which are referred to as the 'third sector'. Research organisations are mostly public sector organisations. They are depicted separately in view of their important role in the knowledge-based bioeconomy. The media are also depicted separately in view of their role in political processes. Typically, they are organisations of the private sector. Citizens are placed in the centre of the diagram. They are closely interlinked with all sectors, as further discussed below.

The development of the bioeconomy depends on the various interactions among the different actors depicted in Fig. 29.1. The different actors may have converging or conflicting interests, which will result in political and economic processes that may be more or less conducive to the bioeconomy.

29.2.2 Private Enterprises and Business Associations

In a market economy, which is after the fall of the Soviet Union the dominant economic system in most countries of the world, private companies are, next to the consumers, the main actors in the bioeconomy. Bioeconomy products and services are, as indicated in

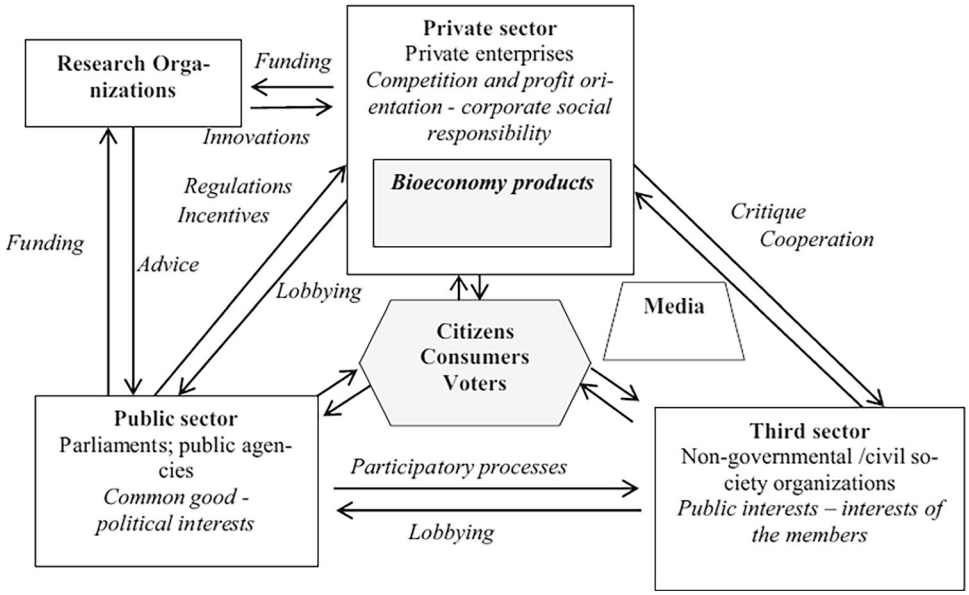


Fig. 29.1 Organisations involved in the bioeconomy and their interactions. (Source: Author)

Fig. 29.1, mostly produced by private companies. They are subject to competition, and they need to make a profit to survive, but they can also exercise corporate social responsibility. An interesting potential of the bioeconomy lies in the fact that the bioeconomy creates new opportunities for a wide range of different types of private sector companies, ranging from the small start-up that explores new biotechnology innovations to the well-established large-scale manufacturers of consumer goods that may decide to introduce bio-based materials.

One of the challenges of bio-based companies is the fact that they are distributed across many different industry branches and that they are, therefore, not represented by traditional industry associations. Companies that engage in the production of bio-based products may even face stiff competition, both economically and politically, from companies that rely on fossil-based resources. However, over time, companies that are engaged in the bioeconomy may form new types of business associations and start to play a role in lobbying for the bioeconomy.

As indicated in Fig. 29.1, bioeconomy companies can benefit from government policies, such as support programmes. The various strategies that governments can use to support the bioeconomy fall under the linkages between private and public sector depicted in Fig. 29.1. Bioeconomy companies may also benefit from research on bioeconomy that is funded by the public sector, and they may co-fund research together with the government. An example is the *Circular Biobased Industry Joint Undertaking* of the European Union (see ▶ Chap. 2, ▶ Sect. 2.3.4.3). Bioeconomy companies and their associations may lobby the government with the aim to induce the government to support the development of the bioeconomy. However, companies that rely on fossil resources may lobby the government, as well, which may slow down the development of the bioeconomy (Barben et al. 2021).

29.2.3 Consumers / Citizens / Voters

In a market economy, consumers are, next to companies, the main economic actors in the bioeconomy. Therefore, policy instruments such as labels for bio-based products can play an important role in promoting the bioeconomy. In the political system, consumers also play a central role as citizens and voters. If they are interested in the bioeconomy, they may consider the extent to which political parties foster the development of the bioeconomy in their voting decision. Citizens may also be critical of the bioeconomy, as the section of critiques of the bioeconomy in ▶ Chap. 2 (▶ Sect. 2.3.3.) shows. Citizens become more effective political actors if they organize themselves in the form of civil society organisations, as discussed in the next section. Figure 29.1 also indicates that citizens are influenced by the media, which may report positively or negatively about the bioeconomy, as is shown, for example, by Dieken and Venghaus (2020).

29.2.4 Public Sector Organisations

Public sector organisations play an essential role in fostering the development of the bioeconomy, since they are required to address market failures and provide suitable conditions or at least a 'level playing field' for the bioeconomy (Barben et al. 2021). Governments can use various policy instruments to promote the bioeconomy, which are further explained in ▶ Sect. 29.3 below. In implementing bioeconomy strategies, the public sector may use the existing public administration or it create special agencies. So far, special agencies have mostly been established for specific components of the bioeconomy, such as renewable resources or biofuels. As further discussed below, the coordination between different ministries and agencies constitutes one of the governance challenges of the bioeconomy.

29.2.5 Research Organisations

Research organisations that carry out basic research related to the bioeconomy are typically public sector organisations, whereas private sector companies play an important role in conducting applied research that leads to bioeconomic products and services entering the market. Public sector research organisations often enjoy a degree of independence that sets them apart from other government agencies. They play an important role in the bioeconomy, especially by conducting research using public funding. They may, however, also receive funding from the private sector and engage in joint research activities. As discussed in ▶ Chap. 37 of this book in more detail, research organisations can involve a wide variety of stakeholders beyond industry partners by applying transdisciplinary research approaches. Members of research organisations may also influence government policies and public opinion by participating in Scientific Advisory Councils related to the bioeconomy.

29.2.6 Third Sector Organisations

Civil society organisations, also referred to as non-governmental organisations (NGOs), play an important role in democratic systems. Since they differ from both public and private organisations in terms of organisational structure and the nature of their interests, they are often referred to as 'third sector'. NGOs typically pursue public interests, such as environmental protection or social justice, which correspond to the interests of their constituents. They are based on principles of collective action and are often organised in networks rather than hierarchical structures. They interact with government, e.g., by lobbying or participating in other ways in policy processes, e.g., by being members of roundtables (see ▶ Sect. 31.2). Since the bioeconomy is still emerging, NGOs that specifically pursue public interests related to the bioeconomy have hardly emerged yet. However, well-established environmental organisations have started to deal with the bioeconomy. As has been pointed out in ▶ Chap. 2 (▶ Sect. 2.3.3), some of them view the bioeconomy rather critically. This is, however, not necessarily an obstacle. To the contrary, by taking a critical perspective, NGOs can play an important function in creating pressure to ensure that the bioeconomy is indeed environmentally sustainable (see ▶ Chap. 2, ▶ Sect. 2.3.4).

29.3 The Process of Developing Bioeconomy Strategies

The diverse actors described in the previous section may be involved in the design and implementation of biodiversity policies or strategies, which are important governance instruments for bioeconomy development, as pointed out above. As explained in ▶ Chap. 2 in more detail, an increasing number of countries have adopted bioeconomy strategies or bioeconomy policies. Since the two terms are often used interchangeably, the term *bioeconomy strategies* is used in the following to refer policy documents or strategy documents that have officially been released by national governments or parliaments. The ▶ Virtual Dashboard on Bioeconomy Strategies by FAO provides a global overview (◘ Fig. 29.2).

The process of developing bioeconomy strategies can take different forms. For example, they may be formulated primarily by government agencies, possibly with the help of scientific advisory bodies. The Food and Agriculture Organization of the United Nations (FAO) has recently published The bioeconomy toolbox: A guide to support the development of sustainable bioeconomy strategies and policies (https://openknowledge.fao.org/items/da351014-0795-4cc7-9e7d-90cfc46685bc). This toolbox clearly recommends a participatory process, which foresees stakeholder participation in all steps of bioeconomy strategy development (◘ Fig. 29.3).

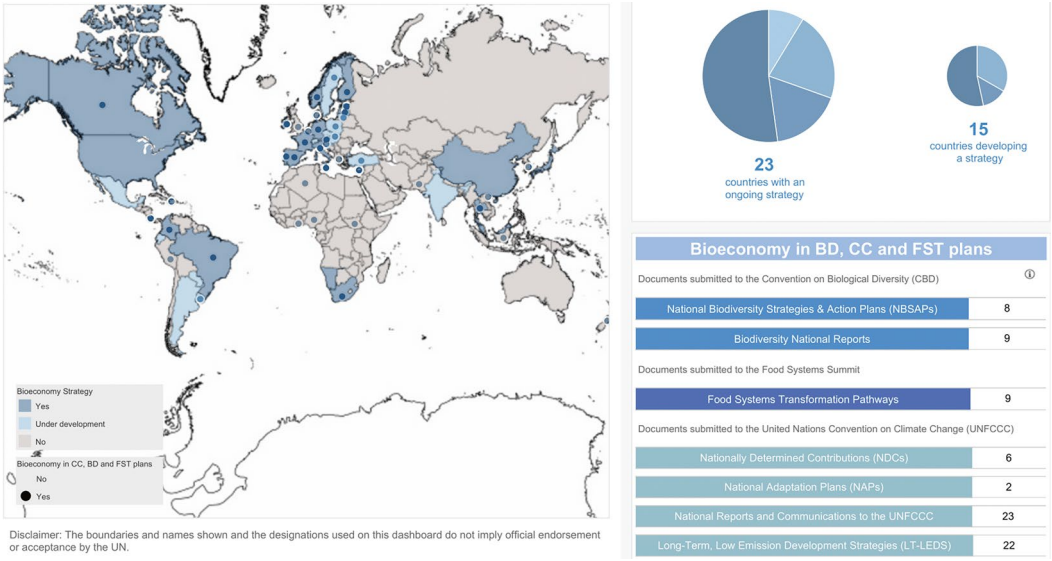


Fig. 29.2 Dashboard on Bioeconomy strategies and related actions for sustainable development by FAO. (© FAO 2023)

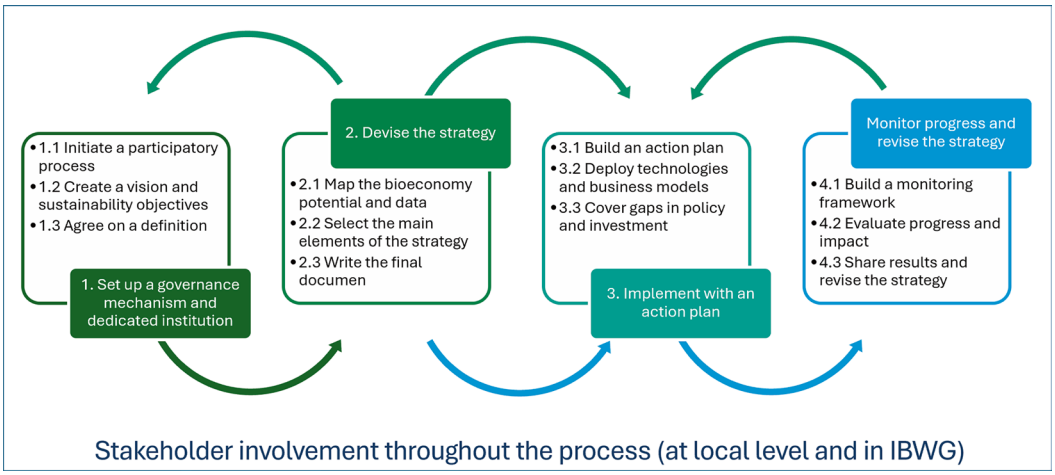


Fig. 29.3 Stepwise approach for the development of sustainable bioeconomy strategies recommended by FAO, adapted from Gomez San Juan (2024, p 12)

To understand the process of developing bioeconomy strategies, one needs to acknowledge that Fig. 29.3. represents an 'ideal' model of such a process, which the actors involved may strive for. One needs to acknowledge, however, that bioeconomy policies and strategies are, inherently, the outcomes of political processes, which are subject to governance challenges caused by differences in world views, conflicts of interests and power structures, as further discussed in ▶ Sect. 29.5.

29.4 Key Elements of Bioeconomy Strategies

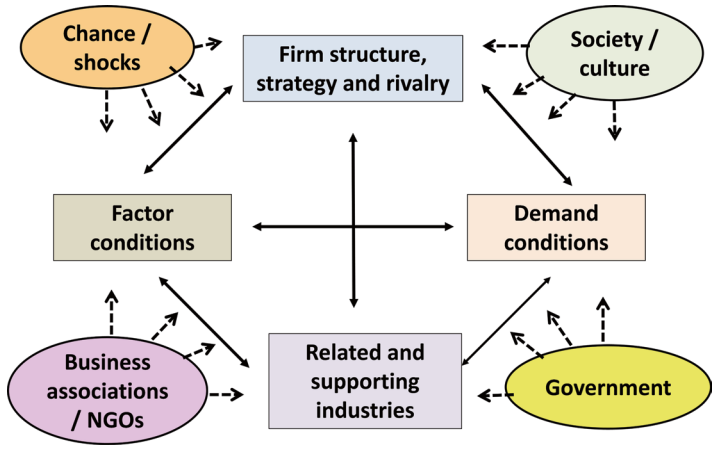
Bioeconomy strategies encompass different instruments that a government aims to use to promote bioeconomy development. They can be classified into different ways. Dietz et al. (2018) distinguish, for example, between supporting and regulating governance instruments. To quote another example, Feindt et al. (2020) use a Resilience Policy Design framework to distinguish design elements of bioeconomy strategies, focusing on energy crops. In this section, a competitiveness framework is applied to identify the key elements of bioeconomy strategies since it allows for a comprehensive and generic classification of the instruments typically found in bioeconomy strategies around the world.

29

29.4.1 A Framework to Identify the Key Elements of a Bioeconomy Strategy

To better understand the bioeconomy strategies that have been developed during the past decades, it is useful to take the comparative advantage into account that a country has for developing its version of the bioeconomy. This comparative advantage is likely to influence the design of bioeconomy strategies. The well-established *diamond model* developed by Porter (1990) provides a conceptual framework, which can be used for determining the competitive advantage of a country's bioeconomy (Birner et al. 2014). ◘ Figure 29.4 displays an adapted version of Porter's diamond model.

The four basic elements of the diamond model, which determine the competitive advantage of a country for developing its bioeconomy, are: (1) factor conditions; (2) demand conditions; (3) firm structure, strategy and rivalry; and (4) related and supporting industries. Bioeconomy strategies typically aim to promote the bioeconomy by targeting several or all of these four groups of factors. The Global Competitiveness Report of the World Economic Forum (2020) provides a wide range of indicators related to these groups of factors for more than 120 countries. Though the indicators are not specific to the bioeconomy, they are still a useful source of information for countries to assess the general conditions for the development of their bioeconomy.



◘ **Fig. 29.4** The Diamond Model of Comparative Advantage. (Source: Adapted from Porter (1990, p 127), published in Birner et al. (2014, p 5))

29.4.2 Upgrading Factor Conditions for the Bioeconomy

Based on Porter (1990), one can distinguish five types of factor conditions, which are relevant for the development of the bioeconomy.

- *Natural conditions*: A country's endowment with land and its agro-climatic conditions have a large influence on a country's competitive advantage for the production of biomass. Countries with large land endowments, favourable agro-climatic conditions and low population density typically have a comparative advantage for emphasising the resource substitution perspective of the bioeconomy (see ▶ Chap. 2), as they have the potential to produce biomass for bioenergy and bio-based materials (e.g., bioplastic) on a large-scale and at comparatively low cost. Brazil, which has a competitive advantage for producing sugar cane, is an example of this type of country. Countries that have access to marine resources may emphasise these resources in their bioeconomy-related strategies. Norway is an example (BÖR 2015b, p 108). Countries with less favourable natural resource conditions and/or limited land resources will have to focus more on biotechnology innovation than on resource substitution to develop their bioeconomy. In recent years, another aspect of a country's natural conditions has gained influence in the design of bioeconomy strategies: the role of biodiversity. Countries with a high level of biodiversity, such as the mega-biodiversity countries of Latin America, have included the sustainable use of biodiversity into their bioeconomic strategies. They feature, for example, the development of inclusive value chains for the sustainable use of non-timber forest products. The national bioeconomy strategies of Colombia, Brazil and Costa Rica feature such strategies (see ▶ Chap. 2, ▶ Sects. 2.3.2 and 2.3.4.4).
- *Labour resources*: While the basic natural conditions cannot be influenced by government interventions, governments can have a large influence on the qualification of their labour force for the bioeconomy, especially by investing in education and professional training. The development of the bioeconomy requires specific skill sets, and education programs need to be adjusted and developed to enable the labour force to gain those skills. As an example, the University of Hohenheim in Stuttgart, Germany, introduced an interdisciplinary Master Program called *Bioeconomy* in 2014. In Porter's framework, such investments in education are referred to as *factor upgrading*, which is an important strategy that countries can use to improve their competitive advantage for the development of their bioeconomy.
- *Knowledge resources*: One of the most important instruments that governments can use to develop their bioeconomy is investment in public research on bioeconomy to foster innovations. The concept of the 'Knowledge-Based Bioeconomy' discussed in ▶ Sect. 2.1.2 emphasises this aspect. Accordingly, investments in research and innovation are an important element of most bioeconomy-related strategies (BÖR 2015a, b; IACGB 2024). Since research by the private sector also plays a key role in developing the bioeconomy, creating a conducive environment for research in the private sector is important, as well. More recent bioeconomy strategies emphasise the role of indigenous knowledge, especially in relation to the conservation and sustainable use of biodiversity, which has resulted in the concept of the socio-biodiversity bioeconomy (see ▶ Chap. 2, ▶ Sects. 2.3.2 and 2.3.4.4).
- *Capital resources*: The development of the bioeconomy relies on investments along the entire value chains for bioeconomy products, including research, product development and marketing. The availability of capital, especially venture capital for risky investments, is therefore an essential condition for the development of the bioeconomy. The recent review of strategies by IACGB in 2024 points to an interesting example of how access to capital resources

can be improved: Finland's bioeconomy strategy entails "partnerships between public and private finance to generate sufficient venture capital" (IACGB 2024, p 28).
– *Infrastructure:* Governments can also support the development of the bioeconomy by providing a supportive infrastructure, especially in terms of transport as well as information and communication technologies (ICTs). An important task is the identification of the infrastructure needs that are particularly important for the specific bioeconomy strategy that a country has designed.

29.4.3 Strengthening the Demand for Bioeconomy Products

An important incentive for the development of the bioeconomy is a strong demand from consumers for bio-based products. Governments can foster this demand by promoting labels for bio-based products that facilitate consumer choice and by conducting information campaigns and fostering social dialogue. Governments can also implement rules for public procurement that strengthen the public demand for bio-based products. The analysis of national economy strategies around the world conducted by the German Bioeconomy Council in preparation of the first Global Bioeconomic Summit (BÖR 2015a) showed that such demand-side instruments have played an important role in many bioeconomy strategies. An interesting example of this approach is the ► BioPreferred® Program of the United States Department of Agriculture (USDA). This program combines a voluntary labelling initiative for bio-based products with mandatory purchasing requirements for federal agencies and their contractors, which encompasses 97 product categories.

The most recent global review of bioeconomy strategies conducted by the IACGB in 2024 shows that demand-side approaches have become more common in recent years. Examples of bioeconomy strategies that promote consumer awareness and demand for bioeconomy products include the European Union, Austria, Finland and Portugal (IACGB 2024).

29.4.4 Fostering Competition Among Bioeconomy Firms

Porter's (1990) analysis shows that a strong competition among companies in their home countries fosters their international competitive advantage because such competition forces them to be innovative and strategic. At times, governments choose to select and subsidise 'champions' and protect them from competition. However, as Porter's comparative historical studies show, this strategy has hardly ever been successful in enabling companies to gain international competitive advantage. This insight can be applied to the bioeconomy, as well. Fostering competition among firms engaged in the bioeconomy and restricting market dominance among them can be seen as an important element of a bioeconomy strategy. The review of bioeconomy strategies by the German Bioeconomy Council in 2015 indicated, however, that this aspect had attracted relatively limited attention so far (BÖR 2015a, b). The review by the IACGB in 2024 showed that, almost a decade later, fostering competition among bioeconomy firms had still not become a major instrument in bioeconomy strategies, yet (IACGB 2024).

29.4.5 Strengthening Bioeconomy Clusters

A striking feature of the bioeconomy strategies around the world is the emphasis that they have placed on the development of clusters, especially in the early phases of promoting the bioeconomy (BÖR 2015a, b). The concept of industry clusters or innovation clusters is based on the insight that the development of the bioeconomy requires a strong and regionally integrated network of industries that are related and supporting each

other along the value chain, e.g. by providing specialised inputs and services. Clusters also benefit from a close interaction of research organisations, start-up companies that are often spin-offs of research organisations and companies that have the capacity to engage in product development and access to large markets. Historical experience indicates that governments have limited capacity to create clusters from scratch. A more promising strategy is to identify emerging clusters and supporting them (Porter 1990). Bioeconomy clusters may also form regional networks. An example is the ▶ 3BI intercluster, a partnership of bioeconomy clusters located in France, Germany, the Netherlands and the United Kingdom. The most recent update of bioeconomy strategies around the world by IACGB (2024) does not highlight the promotion of clusters as a particularly prominent approach any longer, which may be due to a shift in emphasis towards value-chain and demand-side approaches as well as environmental concepts, including circularity and biodiversity.[1]

29.4.6 Using Chances and Shocks as Opportunities for Bioeconomy Development

The comparative historical studies of Porter (1990) have shown that factors that are beyond the control of economic and political actors can play an important role in determining the competitive advantage of an industry. These factors may be positive ('chances'), such as discoveries that offer unexpected opportunities for the bioeconomy, or negative ('shocks'), such as sudden price changes or natural disasters (see ◘ Fig. 29.4). These insights from general economic studies can also be applied to the bioeconomy. Ultimately, it depends on the actions of governments and/or private businesses whether opportunities that arise from chances or shocks are effectively used. For example, the oil price crisis of 1973 induced the Government of Brazil to establish a National Alcohol Program in 1975, which subsequently played an important role in the development of Brazil's sugar-based bioeconomy (cf. Scheiterle et al. 2017). Likewise, the nuclear disaster of Fukushima in 2011 was a major factor behind the political decision of the German government to get out of nuclear energy and focus on renewable energy, a decision referred to as *Energy Turn* (Energiewende). More recently, the COVID-19 pandemic influenced bioeconomy strategies around the world. As the IACGB review of 2024 points out: "The COVID-19 pandemic significantly influenced trends in health-related bioeconomy policy development, a dimension previously received less emphasis. The pandemic also played a role in enhancing supply chain security in bioeconomy-related value chains" (IACGB 2024, p 1).

29.4.7 Considering Sociocultural Factors

As indicated in ◘ Fig. 29.4, sociocultural factors play an important role in the development of the bioeconomy, as well. Just as chances and shocks (see above), these factors are also beyond the immediate control of political or economic actors. Yet, they can influence the development of the bioeconomy in various ways. A case in point is genetically modified organisms (GMOs). Proponents of GMOs argue that they can play an important role in the bioeconomy, e.g., by improving the efficiency of producing or converting biomass. However, in most countries of Europe, the use of GMOs in agriculture is not accepted by consumers, and, therefore, GMOs are not used in agriculture. This exclusion of a technology for sociocultural reasons may, however, foster the efforts to develop alternative technologies, such as crop breeding methods

1 As an indication, the term "circular" or "circularity" appears 32 times in the IACGB global review of bioeconomy strategies, the term "biodiversity" appears 31 times, whereas the term "cluster" does not appear at all (according to a word search in IACGB 2024).

based on statistical methods. Countries may then gain a competitive advantage in such alternative technologies. Another example of role of socio-cultural factors is the concept of the *socio-biodiversity*, which captures the link between the socio-cultural values of local communities and biodiversity conservation. This concept has become important in the bioeconomy strategies of several Latin American countries in recent years (see IACGB 2024 and ▶ Chap. 2, ▶ Sects. 2.3.2 and 2.3.4.4).

29.5 Governance Challenges of Bioeconomy Development

Well-designed bioeconomy strategies, which take the comparative advantage of a country into account, can play an important role in realising the opportunities that bioeconomy holds for reaching national objectives. However, the processes of designing and implementing bioeconomy strategies are confronted with challenges, which are referred to here as *governance challenges*. As can be derived from ◘ Fig. 29.1, the bioeconomy is governed by a network of actors from different sectors that have partly aligned and partly conflicting interests. They interact through a variety of processes, which leads to various governance challenges. They can be grouped into three major types of governance challenges, which are discussed in more detail in the following.

29.5.1 Political Economy Challenges

Governments can play a far-reaching role by creating conducive frame conditions for the development of the bioeconomy, as has been pointed out above. However, as ◘ Fig. 29.1 shows, governments are subject to a variety of forces, such as lobbying by industry groups and civil society organisations, which may have rather diverging views about the bioeconomy. As shown in ▶ Chap. 2 (▶ Sect. 2.3.3), the concept of bioeconomy has been subject to a range of different types of critique. On the one hand, such a critique can create political obstacles to bioeconomy development without offering viable alternative transformation strategies, especially if the critique is fundamental in nature and linked to a more general critique of the market economy or, as it is phrased in this literature, the *capitalist system* (e.g., Birch 2017). On the other hand, the emerging critique of the bioeconomy has helped to overcome important deficits of the evolving concept, especially by addressing well-justified environmental concerns. The process of *greening the bioeconomy* described in ▶ Chap. 2 (▶ Sect. 2.3.4) is an important case in point. Some sub-fields of the bioeconomy have been particularly contested. An example are biofuel policies (see, e.g., Deppermann et al. 2016). Biotechnology regulations, especially regarding GMOs in agriculture, have also been particularly contested early on (see, e.g., Richardson 2012), and remained so, even with the rise of new breeding technologies, such as CRISPR–Cas (see, e.g., Borg and Policante 2025). As a more recent set of case studies from Latin America shows, the design of bioeconomy strategies is influenced by "who takes up the concept, what interests are reflected in this and the implications for socio-environmental concerns" (Siegel et al. 2022, p 541).

Participatory and deliberative policy processes have a considerable potential in improving the policy processes related to the bioeconomy. Mustalahti (2017) presents an interesting recent example from Finland of including citizens in the forest-based bioeconomy with the aim to ensure responsive governance. Likewise, Rodriguez and Prestvik (2020) emphasise "the need for stakeholder engagement and participative governance to promote bioeconomy". To overcome conflicts that are rooted in deep-seated differences in world views, the quality of participatory processes matters. Particularly promising in this context are approaches of 'deliberative democracy', which focus on developing a joint understanding rather than on self-interested bargaining (cf. Evensberg and Fritz 2022; Rieman et al. 2002).

29.5.2 Coordination Challenges

Another challenge of bioeconomy governance is coordination. Since the bioeconomy includes different sectors of the economy, intersectoral coordination is important. It requires collaboration among different ministries, such as the ministries in charge of the economy, agriculture, the environment as well as research and education. Moreover, there is a need to coordinate across different levels. In federally constituted countries, coordination needs arise between the community level, the state level and the federal level. Countries that are part of regional organisations, such as the member states of the EU, also need coordination at supra-national level, resulting in a challenge of multi-level governance (cf Bache et al. 2016).

Germany may serve as an example for the challenge of coordination in the bioeconomy. For intersectoral coordination, the German Federal Government set up an Inter-Ministerial Working Group on Bioeconomy (IMAG) in 2013 under the leadership of the Federal Ministry of Research and Education. Representatives of the federal ministries in charge of foreign affairs, finance, economy, food and agriculture, transport and digital infrastructure and economic cooperation and development joined the IMAG. Its main task was to coordinate the implementation of Germany's Bioeconomy Strategy. A Bioeconomy Council ('Bioökonomierat') to advise the Federal Government was created in 2009 and existed – in three different phases – until 2023. It brought together experts representing different disciplines and different stakeholder groups. Similar coordination and advisory bodies were also created at the state level in Germany (BÖR, 2023), yet a coordination body for multi-level coordination did not emerge. Moreover, even with regard to intersectoral coordination, governance challenges persisted in spite of all coordination efforts (Töller et al. (2021 p 152) analysed bioeconomy policy processes in Germany and the EU and found that "the fragmented institutional and regulatory landscape particularly hinders the establishment of bioeconomy policy as a policy field, as do the ambiguity and inconsistency of its overarching goals as well as its fragile supportive actor constellations".

29.5.3 Global Bioeconomy Governance

Global governance mechanisms for the bioeconomy are essential to address global concerns, such as reconciling food security with an increasing production of biomass and agreeing on joint international standards for ensuring sustainability in the bioeconomy. This challenge of coordination is hampered by the fact that the global governance mechanisms for agricultural development and food and nutrition security have deficits (von Braun and Birner, 2017). yet an effective global governance structure in this field would facilitate the move towards a global governance structure for the bioeconomy. Still, important steps towards global bioeconomy governance have already been made. The creation of the International Advisory Council on Global Bioeconomy (IACGB) and the Global Bioeconomy Summits of 2015, 2018, 2020 and 2024 are a powerful proof that efforts of global coordination of the bioeconomy have taken shape. Still, IACGB has remained a largely informal group, which indicates that global governance mechanisms still need to be further developed. This may require a better integration of the concept of bioeconomy into the global processes related to sustainable development, which are coordinated by the United Nations ▶ Chap. 2 (▶ Sect. 2.3.4.1).

29.6 Conclusion

The term *governance* of the bioeconomy refers to the actors, institutions and processes that are relevant for *steering* the development of the bioeconomy. Such a *steering* is necessary to utilize the full potential that the bioeconomy holds for promoting sustainable development. On the one hand, there is a need to create conducive frame conditions for the bioeconomy,

e.g., by investing in bioeocnomy research and education or by stimulating demand for bioeconomy products and services. On the other hand, regulation may be required to achieve sustainability goals as the bioeconomy is not 'automatically' sustainable.

Bioeconomy strategies are important governance instruments that many countries have put in place to identify the tools that they will use to promote the development of their bioeconomy. The development and implementation of such bioeocnomy strategies is confronted with political obstacles, which may be overcome by promoting participatory and deliberative policy processes. There is also a need to overcome coordination challenges across sectors and multiple levels of government in order to promote the bioeconomic effectively. As the concept of the bioeconomy is not static, but constantly evolving, the governance of the bioeconomy needs to constantly evolve, as well.

29

Questions

1. What are the policy instruments that governments can use to promote the development of the bioeconomy?
2. Who are the main actors in the bioeconomy and through which types of processes do they interact with each other?
3. What are some challenges regarding the governance of the bioeconomy?

Answers

1. Policy or governance instruments that governments can use to promote the bioeconomy can be divided into two broad groups: supporting and regulating instruments. Many governments have developed bioeconomy strategies that specify the tools that a government will use. The competitiveness framework of Michael Porter (1990) can be used to identify key elements of such bioeconomy strategies. They include investment in research, education and infrastructure in support of the bioeconomy (*factor upgrading*), creating demand for bioeconomy products and supporting bioeconomy clusters.
2. The actors involved in the bioeconomy can be divided into organizations of the public, the private and the third sector. Important bioeconomy activities, such as the development, production and marketing of bioeconomy products, are carried out by a wide range of private sector actors, ranging from small-scale farmers to start-ups and, ultimately, multi-national companies. Public sector organisations, including research organisations, can create a conducive policy framework, e.g., by providing public goods and infrastructure that support bioeconomy development. They can also regulate the private sector, e.g., to promote sustainability goals. Civil society organizations can serve a 'watchdog' function with regard to both public and private sector organisations, e.g., through campaigning and lobbying. The media also play an important role by promoting a public discourse on the bioeconomy. The citizens can be seen in the center of bioeconomy governance, since they have multiple roles as consumers as well as voters.
3. One governance challenge is overcoming political economy obstacles, which arise due to divergent worldviews and economic and political interests of different actors. Participatory and deliberative approaches can help to overcome such obstacles, and they also contribute to the evolution of the bioeconomy concepts. Another governance challenge is coordination across sectors and across different levels of governance. Interministerial working groups are one approach to address this challenge. Coordination challenges also occur at the global level. This challenge has be addressed by creating global coordination bodies, such as the IACGB, and organizing global conferences, such as the Global Bioeconomy Summits. Integrating the bioeconomy more explicitly into UN processes is important to further promote coordination at the global level.

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The Role of Farmers and Farmer Associations

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Fig. 30.0 The role of farmers and farmer associations. (© Universität Hohenheim, Max Kovalenko) (► https://doi.org/10.1007/000-hvb)

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Over recent decades, the political, social, legal, and economic landscape of agricultural production has undergone profound transformation at global, European, national, and regional levels. The pursuit of sustainability, coupled with rising expectations for product quality and increasingly stringent standards governing environmental stewardship, animal welfare, and consumer protection, compels farmers to reassess and redefine their development strategies for long-term viability. These sweeping changes, set against the backdrop of intensifying competition within the agricultural sector, have escalated pressures on individual farms. Farmers face mounting challenges, including constrained access to capital, shrinking profit margins, and declining incomes. These difficulties are further exacerbated by the volatility of global markets, where unpredictable price fluctuations add another layer of uncertainty to agricultural operations (De Wolf and Schoorlemmer 2008). Medium- and long-term strategies, both at the individual and inter-farm levels, are indispensable for addressing the escalating competitive pressures in agricultural markets and positioning farms for a sustainable future. At the individual level, particularly within the globally acclaimed family-run farm model, profit maximization is only one aspect of a broader objective: the holistic maximization of benefits for the family. The theoretical principles underlying this approach are explored in detail in ► Sect. 30.1.1. At the inter-farm level, significant opportunities for growth and development emerge through collaboration. Such partnerships can range from targeted cooperation in specific areas—such as shared supply chains, joint marketing efforts, or pooled use of machinery—to the formation of formalised Farmer Associations or cooperatives (Doluschitz et al. 2011). Cooperatives often arise in response to shared challenges that cannot be effectively tackled by individuals alone, echoing Friedrich Wilhelm Raiffeisen's enduring principle: "What is impossible for the individual can be achieved by the many" (Friedrich Wilhelm Raiffeisen 1818–88). Farmer associations, operating at both national and international levels, provide structured mechanisms for collective action, enabling farms to pool resources, enhance efficiency, and amplify their bargaining power. These collaborative models and their practical applications are examined in ► Sect. 30.1.2. By fostering cooperation, farmers can not only adapt to competitive pressures but also build resilience and secure a sustainable future for their enterprises.

30

Learning Objectives

After studying this chapter, you will…

- …be able to explain how agricultural firms operate to maximise their utility (see ► Sect. 30.1.1)
- …be able to derive the concept of profit maximization from microeconomic principles (► Sect. 30.1.1).
- …be able to explain the rationale behind the establishment of farmer associations (see ► Sect. 30.1.2).
- …be able to describe the motivations for farmers to join a farmer association (see ► Sect. 30.1.2).
- …be able to provide examples of farmer associations in high-income countries (see ► Sect. 30.1.2).
- …be able to present an example of a farmer association in low-income countries (see Sect. 30.1.2).

Farmers play a crucial role as stakeholders in the bioeconomy, as they are the major primary producers of the biomass required, in particular to provide sufficient and healthy food for a growing population. At the same time, they are responsible for the management of around 33% (about 4,900 Mha) of the Earth's land surface. They provide not only the essential resources but also the expertise needed for the production of bio-based goods and drive the development of sustainable practices, local innovation and rural economic growth. Empowering farmers and supporting farmer organizations is key to a successful transition to a bioeconomy. It is their knowledge, skills and willingness that determine the sustainability of land management and the well-being of the 2.5 billion people who depend on agriculture for their livelihoods.

There are more than 570 million farms in the world, of which 475 million are smaller

than 2 hectares and are therefore considered smallholdings, and 500 million are family farms (Lowder et al. 2016). Although there is a considerable degree of overlap between the two categories of smallholdings and family farms, they are not the same.

According to the FAO, *family farming* is "a means of organizing agricultural, forestry, fisheries, pastoral and aquaculture production which is managed and operated by a family and predominantly reliant on family capital and labour, including both women's and men's. The family and the farm are linked, co-evolve and combine economic, environmental, social and cultural functions" (FAO 2024).

There are different forms of family farms: those that are managed and operated by a household and where the farm labour is largely provided by that household, and others that make use of paid labour.

Family farms produce more than 80% of the world's food in value terms and operate about 75% of the world's agricultural land. Smallholders farm only 12% of the world's agricultural land (Lowder et al. 2016) (see Fig. 30.1).

Lowder et al. (2016) assessed the farm size for a sample of 111 countries and territories with a total of nearly 460 million farms (Fig. 30.2). They found that 72% of the farms are smaller than one hectare, 12% are 1–2 ha, 10% are between 2 and 5 ha, and 6% of farms worldwide are larger than 5 ha.

Farm sizes are larger in countries with higher average incomes than in countries with lower incomes. For example, farms larger than 5 ha in size account for 27% of the agricultural area in low-income countries, 43% in lower-middle-income countries, 96% in upper-middle-income countries and 97% in high-income countries (Lowder et al. 2016).

This chapter describes the heterogeneous stakeholder group of farmers and the different roles they play in the bioeconomy. They are primary producers at the beginning of bio-

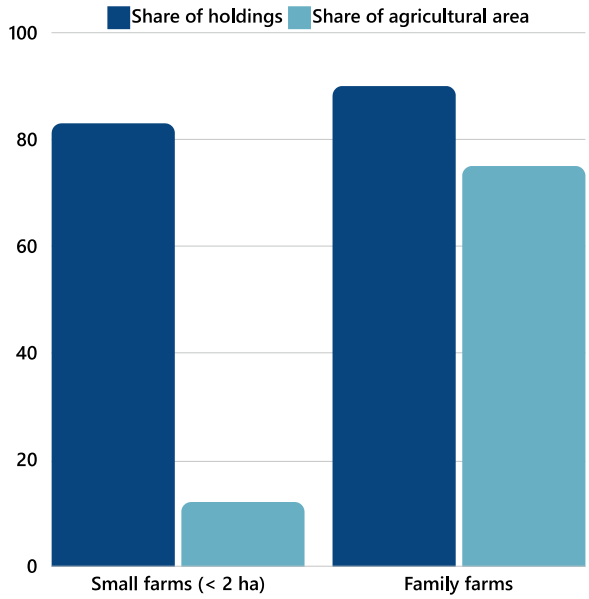
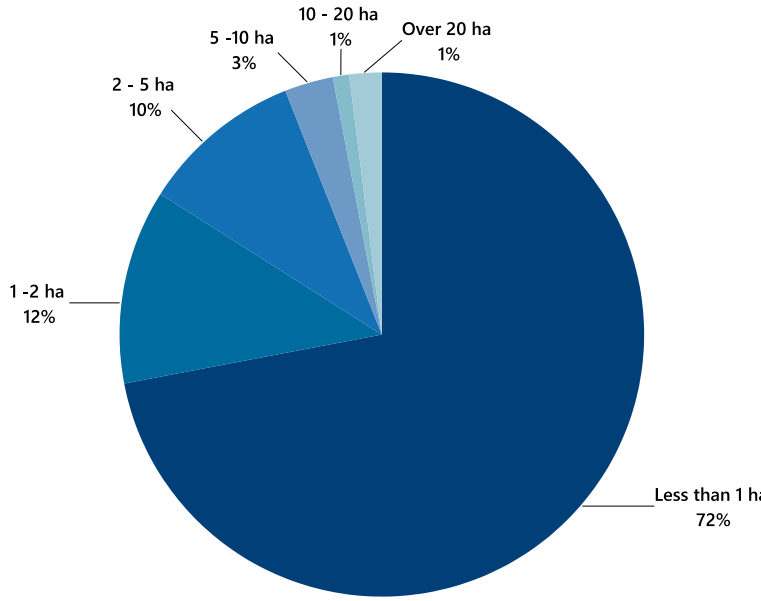


Fig. 30.1 Share of holdings and the agricultural area operated by them, based on Lowder et al. (2016)



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Fig. 30.2 Percentage of farms worldwide by land size class, based on Lowder et al. (2016)

based value chains and thus at the lower end of the value creation channel. Their power depends on access to land and markets for their products. Therefore, farmer associations can be an important lever for the empowerment of farmers, as described in ▶ Sect. 30.3.

30.1 The Role of Farmers and Farmer Associations

30.1.1 The Role of Farmers

30.1.1.1 Farming as Business

The neoclassical microeconomics divides the economic subjects into firms and consumers. Firms maximise their profit with a given production technology and households maximise their benefit with a given preference structure. However, a very large part of the people working in global agricultural production is part of an agricultural household or so-called family business.

When making a production decision for a family-run farm, the profit maximization can be mapped as part of a higher level benefit maximization of the family. The model by Becker (1974) can serve as a starting point for this. A similar approach is also known as a household production model. In line with this modelling approach, we assume that the personal benefit U of a farmer i can be described as a function of the goods he consumes Ym (for 1, …, m goods), which includes both market goods and non-marketable goods (such as leisure):

$$U_i = u_i\left(Y_1, Y_2, \ldots, Y_m\right) \tag{30.1}$$

The production quantity can be expressed as monetary profit and is directly included in the utility function (30.1) in the form of monetary consumption options, which can be exchanged for other consumer goods on the market. The production of agricultural products, in turn, follows a production function (= production technology):

$$Y_j = f_j^i\left(x_1, \ldots x_k, t_j^i, E^i, R_j^i\right) \tag{30.2}$$

Yj is the amount of production that is available as a monetary profit. The first term in Eq. (30.2) is formed by the classic inputs such as wage labour, feed, capital, etc. Time t refers to the personal opportunity costs

between the use of family work in agricultural production, for other sources of income, or for the consumption of non-marketable goods (such as leisure time).

The production function of farmer *i* in Eq. (30.2) has two further vectors, which determine the conversion of the inputs into agricultural products and thus the operational supply quantity:

Ei is a vector of environmental variables that intrinsically influence the production process. These environmental variables are formed by the performance of the ecosystem. For example, location A can be more beneficial for overall productivity than location B. These environmental factors are not technical inputs for the production process but do influence the technical efficiency of these inputs. In addition to natural factors Ei, some aspects increase the farmer's intrinsic motivation. Personal enthusiasm for working on the farm can be part of this vector and lead to an increase in the quality of the work and thus the efficiency of the use of factors.

R_j^i is, according to Becker (1974), a vector of social influencing factors that can also influence farmer i's production decision. Such social influencing factors can also influence supply behaviour, for example, if the firm was taken over as a traditional obligation in the sense of family inheritance but was not managed successfully. Social adjustment pressure can lead to path dependencies and could, for example, accelerate the task of agriculture in crisis situations, or alternatively motivating people to persevere longer than would be economically reasonable ("I do not want to be the last family member who runs the farm"). When it comes to leaving agriculture, the farmer has the choice between continuing his work in the familiar social environment, and a job that may be better paid in monetary terms, which would change the social status. Equations (30.1) and (30.2) show that the decision depends not only on the monetary yield of agriculture but on the personal benefit differential of both alternatives and thus on the individual opportunity costs.

This can explain why in many regions it is observed that farmers "stick to the clod": A large part of the farmers generate permanent equity losses, but agricultural insolvencies are rare, i.e., Equity is consumed or a small salary for family work is accepted. Farmers have a special appreciation (preferences, Eq. 30.1) for the maintenance of farms and agricultural activity.

Maximising profit as part of the overarching maximization of benefits, therefore, plays a special role for changes in the price relationships in agricultural markets, since the supply reactions of agricultural holdings are difficult to assess, particularly when prices fall.

In many regions, farms have very heterogeneous production technologies. Also, not all firms work with maximum technical efficiency or operate in the size range of increasing economies of scale or falling average costs. The short-term and long-term supply behaviour of agricultural firms can, therefore, not always be illustrated using neoclassical microeconomic production and cost functions, and marginal costs are not necessarily the supply-determining economic target variable on which an agricultural firm bases its production decision. The following consideration should illustrate this

It is known that a firm's short-term production threshold is reached when the market price (P) of the goods produced (Q) falls below the average variable production costs (AVC) per unit. The minimum of the average variable production costs (AVC) has an intersection with the marginal cost curve (MC). Above this minimum, the marginal cost curve (MC) theoretically forms the firm's supply curve.

30.1.1.2 Farmers' Different Roles in the Bioeconomy

The roles of farmers in the bioeconomy are manifold and include:

- **Farmers as producers and suppliers of food and biomass include**

As primary producers, farmers are responsible for growing most of the biomass used for food and feed. They also supply the bioeconomy with raw material for a wide range of bio-based products and bioenergy. Farm-

ers represent the first link in bioeconomy value chains.

Farmers as biomass processors

Biomass pre-processing and conditioning start in the field during harvesting, for example, when cereal crops are separated into grain and straw fractions and when straw is baled. Other examples of on-farm biomass processing include the production of silage to make wet biomass storable and the retting of flax straw in the field to make it more accessible for fibre extraction.

In the bioeconomy, farmers have a greater role to play than just supplying biomass, and a broader transition is required to move farmers up the value chain to ensure that local knowledge contributes to innovation and that farmers can become bio-processors rather than simply suppliers of low-cost biomass (Harrahill et al. 2023). Farmers could be involved in processing biomass into higher value-added products through on-farm biorefinery approaches (see ► Chap. 17). Biogas plants are an example of a simple biorefinery technology. In Germany, for instance, there are about 9600 on-farm biogas plants, most of which are equipped with a combined heat and power (CHP) unit for the production of electricity and heat.

Farmers as implementers of sustainable agricultural practices

The extent to which the economic goals of farming can be balanced with social and ecological goals depends above all on the training, ability and willingness of farmers to adopt sustainable agricultural practices (see also ► Chap. 31). Traditionally, farmers have sought to maintain their most important production resource, soil fertility, through appropriate management measures (see ► Sect. 6.9), including those that reduce soil erosion and maintain or increase soil organic matter and thus soil carbon. In the bioeconomy, the provision of ecosystem services (see Excursus ► 6.4), such as carbon sequestration, regeneration of natural resources and biodiversity enhancement may become new tasks and business opportunities for farmers.

Farmers as drivers of a sustainable and circular bioeconomy (food) system

Farmers can also integrate circularity into their operations. By incorporating biogas plants in their farming systems, they can make use of organic residues and animal manure. Using these materials as biogas feedstock reduces emissions and plant nutrients can be recycled as fertilisers. Farmers can adopt bio-based alternatives to traditional inputs, such as bio-fertilisers, bio-pesticides and bio-stimulants, thus reducing dependence on synthetic chemicals and fertilisers, which are largely external inputs to agricultural production systems. They are increasingly becoming producers of quality food, including specialty and traditional foods, in the context of short agri-food chains. This involves new business models, such as farm shops, and strengthens consumer trust through the greater proximity of customers to producers.

Farmers as custodians of local knowledge and innovators

Local farmers have adapted agricultural practices to regional conditions, supporting the development of localised and tailored solutions (see ► Sect. 5.1.2). Farmers, therefore, have valuable traditional knowledge on regionally adapted farming practices and sustainable agro-ecosystem management (see ► Sect. 6.2). Integrating this knowledge into modern bioeconomy strategies can enhance sustainability and resilience (Schmid et al. 2012). In addition, farmers can contribute to innovation in the agricultural and food sector, for example, through co-creation of knowledge. This should mobilise local and tacit knowledge, with innovation seen as a bottom-up, interactive social process, rather than a top-down process from science to implementation. Even highly technical innovations are socially embedded in a process involving clients and

advisors, but it is ultimately the farmers who have to implement the innovations (EU SCAR 2012: 101).

- **Farmers as managers of landscapes**

Landscapes are significantly shaped by agricultural systems. As shown in ▶ Sect. 6.10 for livestock production, these systems are the result of a long evolution. People have become accustomed to the surrounding landscapes and therefore often perceive them as culturally valuable. Farmers are not only able to maintain these cultural landscapes, but they can also change them. Such changes can be perceived negatively, for example, when traditionally grown crops are replaced or when fields are enlarged. An example of a negatively perceived landscape change is the increased production of tall maize as feedstock for biogas plants in Germany. On the other hand, the introduction of multi-flowering wild plant mixtures as a biogas substrate is seen as a positive contribution to the landscape.

- **Farmers as contributors to rural development**

Farmers have an important role to play in rural development as they can bring innovation and new green businesses to rural regions, whether in the areas of agriculture, food and biomass processing, or the provision of ecosystem services. Enhancing landscape value and quality of life in rural areas is also a contribution that can lay the foundation for other agricultural activities such as agritourism (Schmid et al. 2012).

- **Farmers as enablers of the nexus between nature and industry**

Farmers are the managers and custodians of the natural resources that provide the biomass feedstock for the bioeconomy. They are the first link in the bioeconomy value chain, and it depends on them whether biomass resources are supplied sustainably. Therefore, the biomass processors and users in the value chain need to engage and communicate with each other.

30.1.2 The Role of Farmer Associations

30.1.2.1 General Introduction

The internationalization of markets has led to farmers encountering large multinational corporations and volatile prices on global markets (von Witzke 2000; Nüssel 2006; Stappel 2019). This results in an imbalance: small-scale farms are negotiating with consolidated processing and retail companies (European Commission n.d.). In order to remain competitive as independent producers of agricultural and fishery products, farmers voluntarily form associations ((Regulation (EU) No 1308/2013, AgrarOLkG 2024). Horizontal mergers, such as those seen in farmer associations, reduce transaction costs (Valentinov 2007) and strengthen the bargaining position of farmers by:

- enabling the "bundling of supply",
- improving "marketing",
- providing "technical and logistical" services to members,
- promoting "quality management", and
- facilitating "knowledge transfer." (European Commission n.d.)

The legal framework for producer organisations at EU level is based in particular on Regulation (EU) No 1308/2013 (CMO) (Regulation (EU) No 1308/2013), which is implemented in the Member States through national legislation, such as the German Agricultural Market Structure Act (AgrarOLkG). The establishment of a farmer association as a legal entity requires the independent initiation of at least five active individuals association under either private or public law (AgrarOLkV 2023), with this minimum number of founding members being illustrated here by reference to the German legal framework as an example. In this context, various legal forms may be considered, including public law corporations, as well as registered associations, public limited companies, limited liability companies or cooperatives. Furthermore, farmer associations are

Case Study 1: High Income Countries

The European Union is an important global player in agricultural markets and markets for processed food products. The structure of its agri-food value chains is furthermore similar to other developed countries. For instance, in 2016, 10.5 million farms were identified in Europe. Of these, 96% are family-run farms (Eurostat 2021). European farmer associations are important in the areas of fruit and vegetables as well as milk and dairy products (European Commission 2019). This can be explained by price volatility in increasingly global markets. Producer organisations like cooperatives enable the marketing of bundled products and to get a stable price for them. Most producer organizations were identified in Germany and France in 2017 (European Commission 2019). Over a quarter of German producer organizations operate as cooperatives, compared to 60% in France (European Commission 2019).

In high-income countries, farmer associations present an innovative opportunity to integrate agricultural production businesses with the provision of public goods, such as biodiversity preservation and species protection. This approach addresses the contemporary global challenges of resource scarcity in the agri-food sector while simultaneously responding to the urgent need for environmental protection and conservation.

An example of such a multifunctional farmer association is the *Emschergenossenschaft Lippeverband* (EGLV n.d.), which was established to support the preservation of water management areas and ecosystem services. For 90 years, it has operated as the largest wastewater disposal and treatment plant company in Germany. This approach allows for the concurrent achievement of economic and environmental objectives. The association integrates semi-natural grazing systems, orchard meadows and nature-based tourism, thereby adding monetary value to these initiatives. The products generated are marketed locally, facilitating synergies among sustainability, regionality and economic viability.

Another example of a farmer association is *Bunde Wischen e.G.* located in northern Germany (Bunde Wischen eG n.d.). This agricultural organization combines cattle farming through extensive grazing systems with landscape conservation measures. Focused on biodiversity preservation, the association manages a herd of 900 Galloway cattle that graze in conservation areas. The beef produced is sold at the farm store and distributed to several supermarkets, organic markets, direct consumers and the gastronomy sector. Consequently, the association operates as a regional food supplier that harmonises economic and ecological sustainability goals while contributing to landscape preservation and biodiversity.

These examples illustrate that farmer associations are capable of designing and implementing large-scale projects that promote alternative forms of agricultural management aimed at ecological sustainability. They successfully combine a broader regional reach and influence with localised marketing structures. Thus, farmer associations can effectively align society's demand for regional products and proximity to producers with the economies of scale and competitiveness inherent in large-scale economic development.

Case Study 2: Low-Income Countries

In low-income countries, agriculture is predominantly sustained by smallholder farmers, whose livelihoods are intimately tied to the land they cultivate. These farmers hold a pivotal role in global food production and contribute significantly to the preservation of natural resources. Yet, they frequently lack the financial means necessary to enhance their productivity, elevate their incomes and ensure their own food security. Their plight is compounded by formidable challenges, including climate change, disease outbreaks, market volatility and economic instability (Van Touch et al. 2024). The consequences of these challenges are profound and have far-reaching effects on food security, sustainable development and poverty reduction (Olayide and Alabi 2013). A promising approach to mitigating these challenges lies in the formation of farmer associations, which range from informal cooperatives to formalised organizations. These associations address a spectrum of economic, social and technical issues, and their benefits are well documented. The literature indicates that farming households who join cooperatives or farmers' associations benefit from mutual support while gaining access to subsidized agricultural inputs and services provided by governments and non-governmental organizations. These advantages stem from the social capital fostered by cooperatives, which contribute to significantly enhanced farm efficiency and greater household resilience (Francesconi et al. 2023). Women, in particular, have benefited, achieving better market prices for their goods and expanding their production capabilities (Matchaya and Perotin 2013; Serra and Davidson 2020).

Notably, the role of agricultural cooperatives in low-income regions, such as sub-Saharan Africa, diverges markedly from that of their counterparts in Europe or North America. In Europe and the United States, agricultural cooperatives primarily serve commercial or market-oriented functions, whereas in sub-Saharan Africa, they tend to focus on addressing more fundamental needs (Francesconi et al. 2023).

As part of various programmes, such as the Global Agriculture & Food Security Program (GAFSP), the International Fund for Agricultural Development (IFAD) and the Food and Agriculture Organization (FAO), farmer associations are being established and supported. In particular, IFAD describes the positive potential as follows:

> "By coming together in farmers' organizations, market associations and cooperatives, farmers and rural producers can
> increase their productivity and profitability
> gain access to resources, services and markets
> collectively purchase inputs and use infrastructure, thereby reducing the price
> aggregate their produce to reach larger markets
> exchange knowledge and share assets, such as machinery". (IFAD n.d.).

EcoFarm (2024) serves as an exemplary model of a cooperative in a low-income country, seamlessly integrating support for farmers with a commitment to sustainable and ecological objectives.

exempt from cartel prohibitions (AgrarOLkG 2024), allowing them to engage in agreements regarding the quantity and price of agricultural and fishery products within the association.

Case Study 1 and Case Study 2 provide examples of farmer associations in both high- and low-income countries to demonstrate how innovative business models can combine economic and environmental benefits in agricultural production.

30.1.3 EcoFarm Moçambique Lda.

30.1.3.1 Objectives

EcoFarm defines success in terms of specific social, environmental and commercial impact (EcoFarm 2024):

- **People:** Create food security, sources of income and faith in a better future for small-scale farmers, by providing irrigation infrastructure, know-how and market access for cash crops.
- **Planet:** Absorb carbon and nurture biodiversity. Enrich soils through minimum tillage, co-planting and composting. Gainfully use all by-products and waste from agriculture and milling.
- **Profit:** Make the social and environmental impact sustainable by generating profit from exports of high-quality Single Origin Organic Cane Sugar.

30.1.3.2 Impact

EcoFarm's mission is to facilitate sustainable economic growth in local communities through the provision of food security, training, a cash crop and adherence to high environmental standards.

With nearly 600 employees, complemented by seasonal harvest workers, EcoFarm stands as the largest employer in the Chemba region. Additionally, over 500 households participate in sugarcane cultivation, guided by experienced managers. The enterprise integrates a commercial farm with two cooperatives, encompassing more than 500 smallholder families. The impact of EcoFarm is far-reaching and multifaceted. By introducing Brahman bulls, the quality of local cattle herds has been enhanced. Water infrastructure has been extended to serve nearby communities, while education and public health initiatives are actively promoted. Remarkably, since EcoFarm's establishment, the return of antelope to the region has signalled a positive shift in the local ecosystem.

30.1.3.3 Biodiversity

Over half of EcoFarm's total land is dedicated to natural conservation areas, carefully preserved to protect the environment. These conservation zones are shielded from the damaging effects of bushfires using methods akin to those applied to farmland. Designated as "limited-go" zones, these areas allow native flora and fauna to thrive undisturbed, with human activity restricted solely to the management of invasive species that threaten the delicate balance of the native ecosystem.

A harmonious balance of trees and grassland is allowed to develop naturally, creating an efficient system for capturing and sequestering atmospheric carbon dioxide. Within cultivated areas, EcoFarm adopts a comprehensive strategy for soil enhancement. This approach integrates green manuring and the recycling of all agricultural and industrial by-products through composting, nurturing the growth of rich, vibrant and healthy soils.

The integration of limited-go conservation zones and cultivated areas enables EcoFarm to optimise carbon sequestration, achieving a net negative carbon footprint.

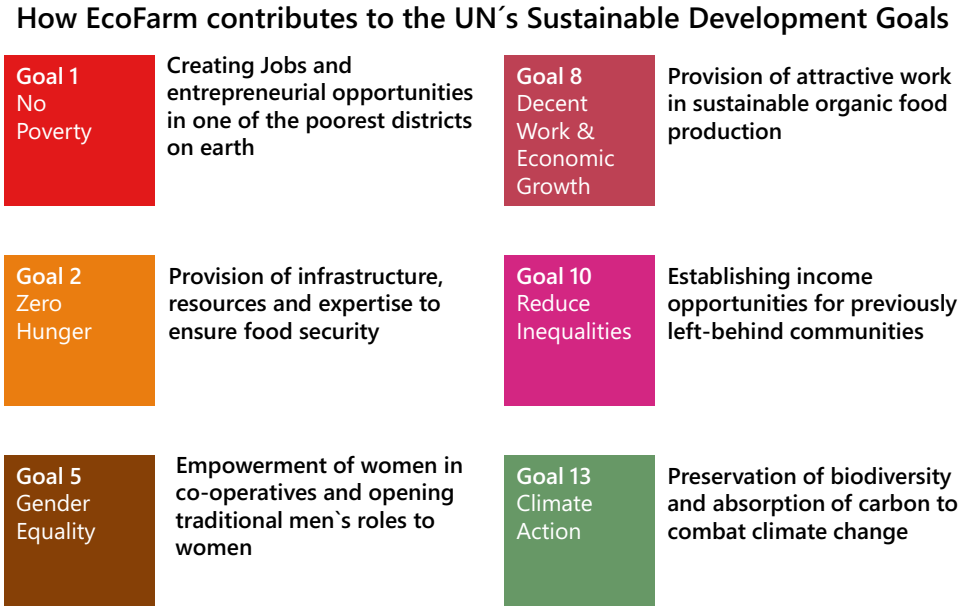


Fig. 30.3 How EcoFarm directly contributes to towards many of the UN's Sustainable Development Goals. Source: Own illustration based on UN SDGs

With the measures outlined, the EcoFarm Cooperative is well positioned to contribute meaningfully to a range of United Nations Sustainable Development Goals (Fig. 30.3).

Questions

1. What challenges do farmers face today? Which individual and inter-farm development strategies can help to meet these challenges?
2. How do producer groups empower their members, and in what ways do they achieve this?
3. What kind of objectives can be targeted by farmer associations in high-income countries?
4. Provide two examples of farmer associations in high-income countries. Explain how economic and environmental goals can be reached and how the farming systems in such models can be characterised.
5. What role can farmers' organizations, market associations and cooperatives play in supporting farmers in low-income countries?

Answers

1. Challenges are intensified competitive conditions in the agricultural sector, rising price and cost pressures at individual farm level. Capital scarcity, declining returns and decreasing incomes in farms. Dynamic market conditions in global markets with high price volatility. Sustainability goals, increasing demands for product quality and increasing standards and regulations for environmental, animal and consumer protection.

   Strategies to meet these challenges include

   (a) Individual farm level: Profit maximization is part of a broader benefit maximization for the family.

   (b) Inter-farm level: cooperation. Collaborations can vary significantly in intensity, ranging from cooperation in specific business areas up to the formation of Farmer Associations or cooperatives.
2. Horizontal associations in the form of producer organisations strengthen farmers, i.e., producers of agricultural

or fishery products. Producer organisations (POs) enable farmers to:
(a) Bundle the agricultural products offered
(b) Enhance marketing
(c) Promote their members through technical and logistical services
(d) Contribute to quality management
(e) Foster knowledge transfer

3. Economic and environmental goals can be reached by farmer associations. Thus, the ability to provide public goods such as the preservation of biodiversity or species protection and a solution to the problem of scarce resources in the agri-food sector and environmental protection and preservation can be provided.
4. *Emschergenossenschaft Lippeverband*: This association focuses on the preservation of water management areas and ecosystem services. By adopting this integrated approach, it achieves both economic and environmental objectives simultaneously. The association combines semi-natural grazing systems, orchard meadows and nature-based tourism, thereby creating additional monetary value. The products generated are marketed locally, fostering synergies among sustainability, regionality and economic viability.

   Bunde Wischen e.G.: This organization harmonises cattle farming through extensive grazing systems with landscape conservation initiatives. It emphasises the preservation of biodiversity by managing cattle grazing in nature conservation areas. The beef produced is sold at the farm store and is also distributed to various supermarkets, organic markets, direct consumers and the gastronomy sector. As such, the association functions as a regional food supplier that integrates economic and ecological sustainability goals, contributing to the preservation of landscapes and biodiversity.
5. The formation of farmers' organizations, market associations and cooperatives enables farmers and rural producers to achieve a number of benefits, including:
(a) Increase their productivity and profitability
(b) Gain access to resources, services and markets
(c) Collectively purchase inputs and use infrastructure, thereby reducing the price
(d) Aggregate their produce to reach larger markets
(e) Exchange knowledge and share assets, such as machinery

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Sustainability Management at Farm Level

Iris Lewandowski and Moritz Wagner



Fig. 31.0 Sustainability management at farm level. (© Universität Hohenheim, Florian Gerlach) (▶ https://doi.org/10.1007/000-hvc)

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Sustainability management at farm level requires, above all, good agricultural practice. Beyond that, sustainability assessment tools such as LCA and criteria-based methods can support farmers in identifying hot spots as well as optimization options for farm management. Certification schemes can help with the assessment, documentation and labelling of sustainability at farm or product level and assist the farmer in marketing the product. Wherever large quantities of data are generated, digital tools can support both process optimization and documentation. Stakeholder collaboration and value chain integration are also important approaches to farm sustainability management.

Learning Objectives

After studying this section, you will…

- …be able to give an account of how sustainability at farm level can be operationalized (see ► Sects. 31.1, 31.2, 31.3, and 31.4).
- …be able to describe how Life-Cycle Assessment (LCA) can support sustainabililty management at farm level (see ► Sect. 31.1).
- …be able to explain how certification schemes work and how they are useful to farmer (see ► Sect. 31.2).
- …be able to provide recommendations for sustainability management approaches at farm level (see ► Sects. 31.1, 31.2, 31.3, and 31.4).

There are various sustainability requirements for biomass production and supply in the bioeconomy (see ◘ Fig. 31.1). These include ecological, economic, social, but also ethical criteria such as food security issues and socially acceptable production methods. Consumers demand a sufficient quantity, quality and reliable supply at reasonable prices. At the same time, biomass production and supply have to be ecologically and socially sound as well as economically viable with fair remuneration for producers. To avoid land use competition, e.g., between food and biomaterials production and biodiversity, and also to avoid indirect land use (iLUC) effects (see ► Sect. 28.4.2), land use has to be efficient. Traditionally, the amount of biomass or agricultural products harvested per unit area is the most important indicator of land use efficiency. In the bioeconomy, the definition of land use efficiency includes consideration of the provision of different and ideally multiple ecosystem services beyond productivity (see Excursus ► 6.4 on ecosystem services). A sustainable biomass supply should also have low greenhouse gas emissions along the supply chain. In terms of efficiency, but also in order to meet ethical requirements, biomass supply chains should be designed to operate along the value pyramid, applying principles of cascading use and circularity. The value pyramid approach prioritizes the use of available biomass for food production. Non-edible biomass components only are applied first for material uses followed by energetic purposes. Biomass production and supply systems should be designed efficiently, for example by reducing food losses. Circularity approaches, such as plant nutrient recycling and biorefinery technologies, should be applied in biomass production and supply systems.

To fulfil these demands, farmers require concepts for assessing and operationalizing sustainability on their farms. In general, sustainable biomass production depends heavily on the way in which production processes are managed. This was described in ► Sect. 6.1 for both crop and livestock production. In addition, ► Sect. 6.11.1 describes the approach of applying management concepts such as organic farming or Good Agricultural Practice (GAP), which are considered operationalization approaches for sustainable agriculture.

For many of the demands on biomass production and supply described in ◘ Fig. 31.1, productivity – indicated by high yields per agricultural area – has traditionally been the most important performance indicator and this is still valid today. Productivity is the ratio between agricultural output, e.g., biomass yield, and the inputs, e.g., land or fertilizer. Sufficient biomass quantities can be best provided through high productivity. Productivity is an indicator of land use efficiency, and a high yield can prevent iLUC effects resulting from additional land requirement for production that cannot be met on existing agricultural land. Thus, the higher the productivity on exist-

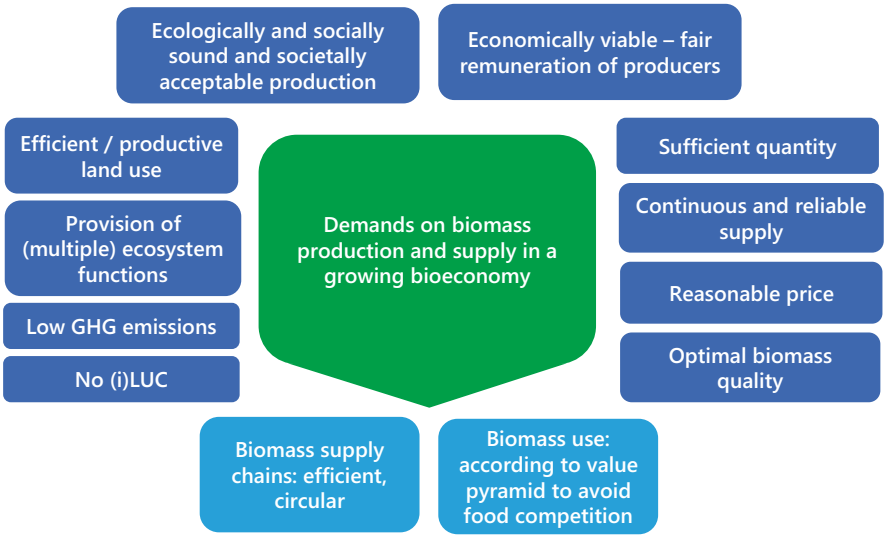


Fig. 31.1 The multiple demands on biomass production and supply in a growing bioeconomy can be characterized as mainly ecologically and socially relevant (blue boxes on the left) or economically relevant (blue boxes on the right). The light blue boxes represent demands arising from integration into the biomass supply chain and biomass use

ing agricultural land, the less additional land is required. However, achieving high yields may involve trade-offs, such as a higher demand for pesticide use. Therefore, fulfilling sustainable production demands requires a more holistic view embracing a range of diverse criteria.

The following subsections describe approaches that can support farmers in sustainable farm management through holistic assessments. These include tools such as life cycle assessment (LCA) and indicator-based frameworks for the assessment of sustainability. This is followed by an account of how certification systems can help in the assessment, documentation and labelling of sustainability at farm or product level, and how digitalization can support both process optimization and documentation. Finally, collaboration between stakeholders within the value chain is introduced as a practical contribution to farm sustainability management.

31.1 Life Cycle Assessment (LCA)

Life cycle assessment is an internationally recognized method for the holistic analysis of potential environmental impacts of products and services over their entire lifecycle, standardized in two ISO norms (14040/14044). A detailed description of the LCA methodology is provided in ▶ Sect. 41.2.1. For sustainability management at the farm level, there are two main applications of the LCA approach. Firstly, the method can be applied to assess the environmental performance of the farm (or of specific products). In this case, the results can be used to identify environmental hotspots and develop optimization strategies to reduce or mitigate these impacts (Fan et al. 2022). As conducting an LCA can be quite complex and time-consuming, several simplified tools have been developed that can be used by non-experts such as practitioners. A widely used example of such a tool is the ▶ Cool Farm Tool. This tool features an integrated database of emissions associated with background processes. These are processes that describe the supply chain, e.g., emissions from fertilizer production, and are secondary data that are difficult for the farmer to assess. The Cool Farm Tool requires farmers to enter information on foreground processes only, i.e., their agricultural activities, such as the amount of fertilizer applied or the amount of biomass harvested. This allows them to assess the impact of their activities on greenhouse gases, biodiversity and water use at farm level.

For instance, farmers can use the tool to gain a deeper insight into the impact of their on-farm management decisions on the carbon cycle, and thus choose management options that reduce greenhouse gas emissions or increase carbon sequestration in the soil.

In addition to the identification of hotspots, the LCA approach can provide an important basis for various existing or emerging sustainability standards and certification schemes, especially as consumers show an increased interest in information on the environmental impact of their food (Hélias et al. 2022).

In what way does the support provided by LCAs for sustainability management differ between farm and corporate level? (see ► Sect. 35.2 on description of sustainability management at corporate level)

31.2 Sustainability Standards and Certification

Various criteria-based instruments are available for advising on and assessing farm sustainability. They generally use indicators that provide quantitative or qualitative information, based on which the performance is judged against sustainability criteria. Either an assessment is made as to whether the indicators fulfil the criterion and a yes/no answer is given. Or indicator values are compared to setpoints or threshold values that must be met, for example, to obtain certification. In this case, the indicator value can also be used to show relative performance, i.e., the extent to which a setpoint is achieved.

Indicators are variables and parameters that describe complex systems and are used to reduce complexities and integrate information. They are intended to provide quantitative and qualitative information on the status and development of systems and thus ultimately serve as decision-making aids.

The functioning of an indicator-based tool can be explained using the example of SAFA—Sustainability Assessment of Food and Agriculture Systems. This is a set of sustainability guidelines published in December 2013 by the Food and Agriculture Organization of the United Nations (FAO). The guidelines define four dimensions of sustainability: good governance, environmental integrity, economic resilience and social well-being. Each dimension is divided into 21 themes and 58 sub-themes associated with explicit sustainability objectives. These translate into criteria that are described by indicators and depicted in a so-called spider web diagram (see Fig. 31.2). The performance for each theme is plotted, and a black line connecting the points indicates the overall performance according to a traffic light colour code: best/good (green), needs improvement (yellow/orange) or unacceptable (red). The performance for each theme is evaluated using a series of indicators for the different sub-themes. For example, the theme "land" has the two sub-themes "soil quality" and "land degradation". Indicators used to describe the performance in these sub-themes are, for example, soil physical structure, soil organic matter, soil degradation and desertification.

In practice, the greatest challenge in the application of this tool is the rating of the performance indicators (see FAO (2013) for example procedures). The assessment is concluded with a performance report that can form the basis for a certification decision or be used to inform customers on the sustainability performance of a farm or an agricultural product. For this performance report, it is important that the calculation process, including rules for aggregation and weighting of indicator values, is described transparently and that all decisions are presented and justified.

The sustainability assessment of food and agriculture systems can: (1) help define sustainable food and agriculture systems, (2) provide a procedure for the integrated analysis of all sustainability dimensions, and (3) describe sustainability themes, sub-themes, goals and indicators (FAO 2013).

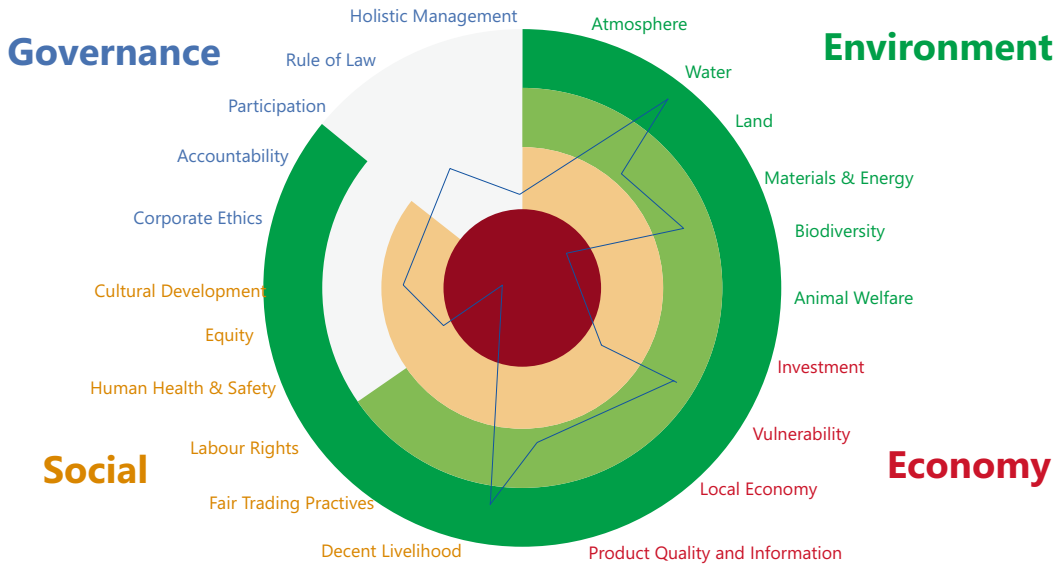


Fig. 31.2 This visualisation depicts the SAFA sustainability performance rating for a hypothetical enterprise. The black line connects the performance of the individual themes according to a traffic light colour code: best/good (green), needs improvement (yellow/orange) or unacceptable (red)

Farmers can use the information provided by these sustainability assessments to identify hotspots and levers for improving farm sustainability, as they help to make them aware of processes on their farms that are not set up optimally. This is often the case with traditionally run processes or habits that receive little or no reflection. In many cases, an improvement of these aspects in the ecological dimension goes hand in hand with an improvement in the economic dimension. Sustainability assessment tools are therefore primarily advisory instruments designed to help farmers improve their business in the long term with respect to sustainability criteria. However, the results can also be used in communication with customers and social groups (Spiller et al. 2023).

Based on the information they provide, SAFAs and other similar criteria-based sustainability assessment tools such as the Response-Inducing Sustainability Evaluation (RISE) or the DLG Sustainability Standard can also provide standards and information for the certification of farms or agricultural products.

Certification systems for agricultural and food products provide assurance (through a certification mechanism) that certain characteristics or attributes of the product or its production method or production system have been met (Chever, Gonçalves, Lepeule - AND International 2022). Farmers are motivated to participate in certification schemes not only to demonstrate compliance with consumer demands, but also for marketing reasons, especially since there is a strong demand pull from retailers who require labelling of food products for marketing. The requirements for certification are:

- A standard describing the objectives or criteria for certification
- A traceability process to ensure the origin of the product
- A process and organizations for the accreditation of certifiers and certifying institutions

A compilation of criteria for sustainable agriculture used in sustainability standards and also for certification by the Roundtable on Sustainable Palm Oil (RSPO), the Round Table on Responsible Soy (RTRS), Bonsucro, and the Roundtable on Sustainable Biomaterials (RSB) is given in ▶ Sect. 6.1. and in ◘ Fig. 6.18. Traceability assurance is

Table 31.1 Examples of certification systems in the agricultural sector

Certification system	Objectives and focus	Contents
Global Gap	Good agricultural practice	Standards "for safe, socially and environmentally responsible farming practices" that can be enhanced with "add-ons" targeting more specific aspects (e.g., animal welfare, integrated production, working conditions etc.). Food safety, an additional module for social sustainability
Rainforest Alliance	Good agricultural practice	Standards for sustainable agriculture
IFOAM USDA organic Naturland	Organic farming	Organic+; standards for organic farming
Roundtable on Sustainable Palm Oil (RSPO)	Sustainable palm oil	Zero deforestation, nature conservation, human rights
Round Table on Responsible Soy Association (RTRS)	Responsibly produced soy beans	Zero deforestation, nature conservation, human rights
Beter Leven Initiative Tierwohl	Animal welfare and health	Promotes greater animal welfare in livestock farming
REDcert ISCC—International Sustainability and Carbon Certification	Climate / low GHG emissions	Focusses on climate change-related issues and promotes measures for GES emission reduction and enhanced carbon storage
VLOG Certification	Non-GMO	Guarantees the absence of GMO ingredients and/or agricultural products in the labelled products

particularly relevant for due diligence and therefore described in ▶ Sect. 35.4. There are different certification schemes for agricultural production at both farm and commodity level and for labelling specific features of the product (see Table 31.1). A detailed analysis of these certification schemes applied in the EU is provided by Chever, Gonçalves, Lepeule - And International (2022).

All of these certification schemes use rules (e.g., for land use, for good agricultural and management practices) that farmers have to apply in order to be certified. Certification can be obtained from various certification bodies that offer certificates for the certification schemes mentioned above. It is up to the farmer to initiate the certification process by approaching the relevant certification body.

31.3 Digitalization

Digitalization can support farm management in a number of ways (see Fig. 31.3), in particular where large amounts of data are generated or where different data sets need to be taken into account (see also ▶ Sect. 15.2 Digitalization in agricultural production). The main challenge is to link these data – which describe different dimensions and have different formats – in a meaningful way, as is usually the case for sustainability assessments.

A practical example of support for the operationalization of sustainable farm management practices can be seen in remote sensing technologies that provide information on the status of the crop stand, e.g., occurrence of pests and diseases or nutritional status, to allow precise, low-emission and efficient application of fertilizer or crop protection mea-

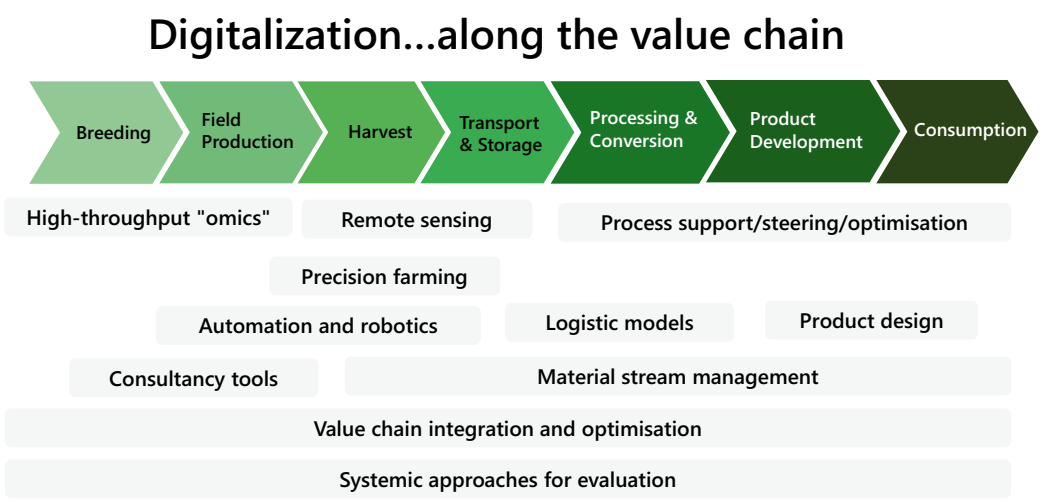


Fig. 31.3 Digital support options in farm management: The green arrows represent the different processes in a bio-based value chain from breeding of the crops, their production, harvest and biomass conversion through to product development and consumption. The bars labelled with digitalisation technologies or the processes they manage stretch over the steps in the value chain that they are support

sures. An example of value chain integration is material flow management, where the composition, quantities and location of biomass production are linked to consumer demand, processing options and possible transport routes.

In the assessment and documentation of sustainability at the farm level, digital tools can support data collection, organization and interpretation to either identify management improvement options or for reporting.

31.4 Collaboration Towards More Integrated Value Chains

Bio-based value chains comprise several processing steps with stakeholders from different sectors and with an increasing product value along the value chain (see Fig. 31.4). Stakeholders involved in primary production, including farmers, are at the beginning of these value chains and thus at the lower end of the value creation channel. An important objective in the bioeconomy is to improve the economic viability of farms by strengthening local value chains and the participation of farmers in the value chain and value creation. Collaboration within the value chain is therefore introduced as the final aspect in farm sustainability management.

Better integrated value chains with greater farmer participation can be driven by farmers themselves, for example by creating opportunities to integrate more process steps on the farm. On-farm biorefinery approaches in particular (see ▶ Chap. 17) provide farmers with technologies to convert their primary biomass into processed biomass components or products that can be sold at a higher value.

Value chain integration can also be driven by the processors collaborating with their suppliers, for example, to achieve a more reliable and fair supply chain. At farm level, this can mean biomass processing companies entering into long-term contracts directly with farmers for the supply of biomass or products. They can also support them in the financing of infrastructure for on-farm (pre-)processing of the biomass.

Farmer organizations (FOs), such as farmer associations (see ▶ Sect. 30.1.2), agricultural cooperatives, producer groups and rural financial cooperatives can significantly strengthen the power of farmers in the value chain. FOs are a key partner for governments in policy development and enable farmers to make their voice heard. As civil society actors, FOs promote democratic engagement and

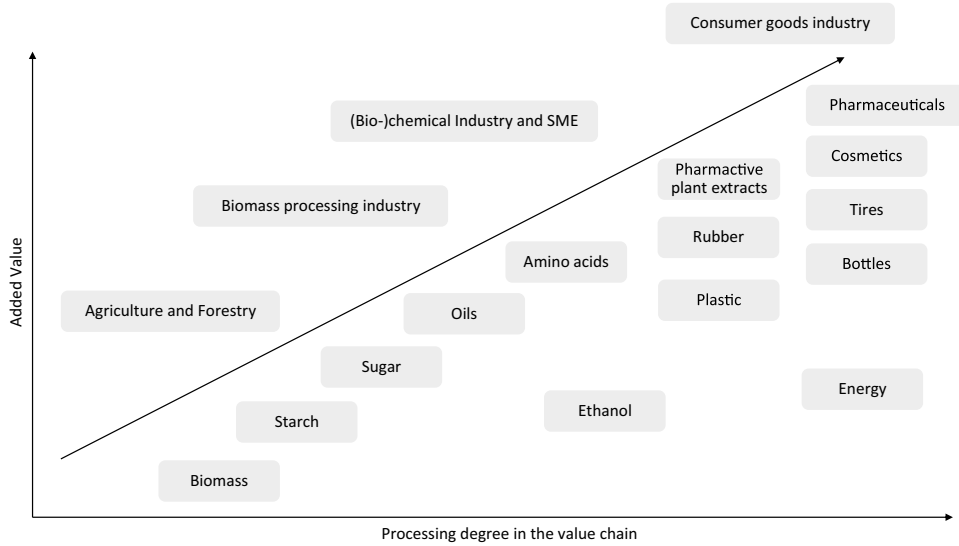


Fig. 31.4 The increase in bioeconomic value creation along the value chain

31

provide opportunities for farmers to participate in political processes. FOs can also establish and maintain contacts with industry and link them to other stakeholders in value chains, while providing their members with information and practical knowledge (Rauch 2023). In the bioeconomy, FOs are best placed to create value and integrate primary producers into efficient and consolidated bio-based value chains, with benefits being fairly distributed among the stakeholders.

Farmer associations often operate as cooperatives, allowing farmers to pool resources, share risks and access larger markets. This increases farmers' bargaining power and facilitates their participation in the bioeconomy. Farmer associations help their members access funding, grants and subsidies for bioeconomy projects. They can also assist with certification processes (e.g., organic, fair trade) that open up additional markets. Farmers need fair remuneration for sustainably produced biomass. Without well-developed markets and fair trading conditions, which can be negotiated by FOs, there is a risk of exploitation or under-pricing. FOs can support farmers and promote their positioning as "price makers" rather than "price takers" (Harrahill et al. 2023).

Overall, FOs can help ensure that the transition to a bioeconomy is just, so that power imbalances in traditional economic sectors are not replicated in a bioeconomy. The concept of *Just Transition* has gained prominence in recent years, particularly in response to sustainability challenges in agricultural production. "*A Just Transition intends to provide an alternative to the perceived trade-off between protecting employment and incomes from unsustainable practices and the need for environmental protection. For a Just Transition to be achieved, consideration is needed for not only the new, sustainable practices in which farmers will participate but also the structure of the value chains in terms of their ability to influence the operation of the bioeconomy and the price they receive for their produce and related activities*" (Harrahill et al. 2023). The role of FOs here could be the same as that of trade unions in achieving a *just transition* for workers by enabling farmers to participate in social dialogue activities related to farm diversification (Harrahill et al. 2023).

Questions

1. Which forms can sustainability management take at the farm level? Give at least two examples.
2. What are the two major applications of the LCA approach at the farm level? How do they support sustainability management at farm level?
3. What are certification systems? What is the main function of certification schemes? What are the requirements for setting up a certification scheme?
4. Imagine the following situation: You are approached by a farmer who asks you how he can improve the environmental performance of his farm. Give one recommendation that could help the farmer achieve his goal. (Note: you do not need to go into detail about the farm's operations).

Answers

1. Possible examples of sustainability management at farm level are:
   (a) Good agricultural management practice
   (b) LCA
   (c) Participation in certification
   (d) Compliance with sustainability standards
   (e) Collaboration within the value chain
2. The two major applications of the LCA approach at farm level are:
   (a) Assessment of the environmental performance of the farm (or specific products) to identify environmental hotspots and develop optimization strategies to reduce/mitigate the impacts, thus increasing the overall sustainability of the farm's operations.
   (b) Provision of a basis for the development of sustainability standards and certification schemes to provide consumers with information on the environmental impacts of their food.
3. Certification systems for agricultural products and food provide assurance (through a certification mechanism) that certain characteristics or attributes of the product or its production method or production system have been met.
   Certification schemes assure customers or business partners that certain characteristics or attributes of the product or its production process/system have been met during production. Participation in certification schemes signals interest in consumer demand and is often necessary to fulfil marketing requirements.
   The requirements for establishing a certification scheme are:
   (a) A standard describing the objectives or criteria for certification
   (b) A traceability process to ensure the origin of the product
   (c) A process and organizations for the accreditation of certifiers and certifying bodies
4. The main recommendation could be to first identify the environmental hotspots of the farming operations. For this purpose, an LCA could be performed. Secondly, the most environmentally relevant management procedures should be targeted for practical improvement.

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Fostering Innovation Systems for the Transition to a Bioeconomy

Andreas Pyka and Klaus Prettner



Fig. 32.0 Fostering innovation systems for the transition to a bioeconomy. (© Universität Hohenheim, Wolfram Scheible) (▶ https://doi.org/10.1007/000-hvd)

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To improve sustainability, the global economic system has to undergo severe transformation processes. This chapter deals with the possibility of an innovation-triggered transformation towards a knowledge-based bioeconomy, which is supposed to overcome the current lock-in into a fossil fuel-based CO_2-intensive production. To do this, a Neo-Schumpeterian view is applied, which highlights the complex interplay in knowledge-generation and diffusion processes between firms, consumers and government institutions. By applying the Neo-Schumpeterian approach, it becomes obvious that innovation and economic growth are part of the solution and not part of the sustainability problem. The shift from quantitative growth to qualitative development makes the difference and affects all agents and institutions in an economic system, which needs to be designed as a dedicated innovation system supporting the transformation towards a knowledge-based bioeconomy.

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Learning Objectives

After studying this chapter, you will…

- …be able to describe the technological, political and social shifts that are necessary to achieve a transformation to a sustainable bio-based economy.
- …be able to assess the differences between the two approaches: *i)* conservation of resources by growth abstinence and *ii)* decoupling of growth and exploitation of resources.
- …be able to explain the foundations of the neo-Schumpeterian framework in the analysis of radical innovations.
- …be able to discuss the challenges, opportunities, and consequences of innovations such as the `sharing economy', `biofuels' and `digitalisation' in the transformation towards a knowledge-based bioeconomy.

32.1 Introduction

The sustainability of modern economic growth, as it developed in the todays' Western industrialized economies from the beginning of the industrial revolution at the end of the eighteenth century, has been questioned at the latest since 1972 when the book *The Limits to Growth* was written by the *Club of Rome* (Meadows et al. 1972). After more than 200 years of industrial production, large parts of the world population are richer than ever before. However, industrial production in its current form is also closely linked with the exploitation of natural resources and the strong accumulation of greenhouse gases in the atmosphere, endangering human survival.

In economics, two fundamentally different solution strategies are discussed as a reaction on man-made climate change and irreversible environmental damages: (i) c*onservation of resources by growth abstinence* and (ii) *decoupling of growth and exploitation of resources*. In this chapter, we show that the first perspective with its emphasis on the efficiency of price competition is not suited to conceive a transformation of the production system towards a knowledge-based bioeconomy. Only the emphasis on the superiority of innovation competition, inherent to the second perspective, allows for the inclusion of the required transformative perspective.

The supporters of the first approach (e.g., Blewitt and Cunningham 2014, Kallis et al. 2014), summarized under the headings of *abstinence* and *downscaling*, claim a renunciation of our lifestyles based on consumption and increasing deployment of resources. This is considered the only way to enable a sustainable and environmental-friendly lifestyle and form of economic activity. At first sight, it might look surprising that these growth-hostile approaches are strictly in line with the thinking put forward in mainstream neo-classical growth theories. This follows from the fact that the standard neo-classical approach relies on the assumption of stable economic structures and an understanding of economic growth as a continuous increase in the quantity of goods that are produced. Figure 32.1 depicts the impressive growth performance of the German economy, where—in particular in the period of the so-called *Wirtschaftswunder* after 1945—income per head skyrocketed: At the beginning of the twenty-first century, per capita GDP is approximately four times higher than three

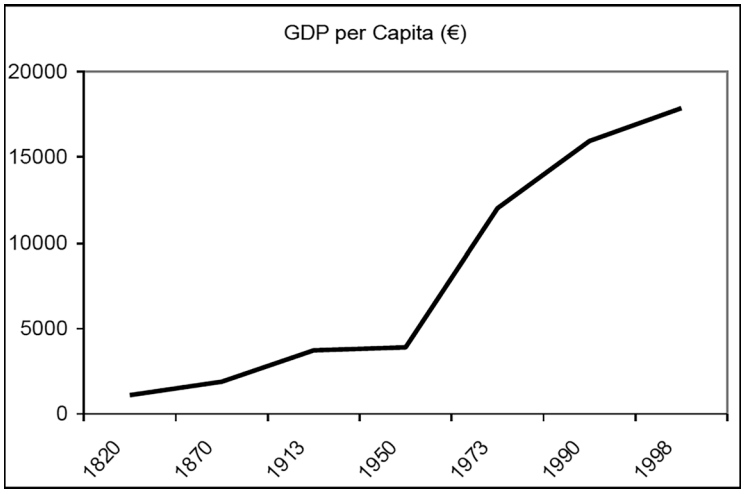


Fig. 32.1 GDP per capita in Germany (Maddison 1995)

generations earlier. But does this mean that German consumers today have four Volkswagen Beetles in their garages? Obviously not! Today we have completely different goods and services in our consumption baskets, we acquire different competences in universities, we work in different jobs etc. Restricting economic growth analysis to a quantitative dimension only, dismisses these most important qualitative dimensions. Such an analysis can only serve for a very short-term observation.

The alternative approach of Neo-Schumpeterian economics (e.g., Hanusch and Pyka 2013) challenges this quantitative orientation and instead emphasizes the importance of qualitative aspects, which make fundamental changes of economic structures over longer periods visible. Without the consideration of the qualitative levels of economic growth, the quantitative figures cannot tell much about the massive technological and socio-economic developments. The Neo-Schumpeterian approach highlights that innovations, market forces, structural change and urban ways of life are both, part of the problem, but also part of the solution to the sustainability problem. Innovation-triggered development generates both, quantitative, i.e. income-increasing growth and qualitative, i.e. structure-changing development. Only the creative solutions characteristic of capitalistic-organized economies will enable to reform our future economy in the sense of sustainability, thereby supporting the UN's sustainability goals and simultaneously ensuring growth and development (Mazzucato and Perez 2015).

The central role of innovation in Neo-Schumpeterian economics highlights that abstinence in the sense of economic downscaling is neither the first nor the only solution. This does not mean that all ideas of the proponents of the camp are rejected: In perfect accordance, certain past patterns like the high '*energy-intensity*' of production because of too low oil prices not covering the total environmental costs or so-called '*planned obsolescence*' in consumption require urgent adjustments. Especially, concepts resulting in a more intensive use of goods and therefore contributing to the economization of resources like the '*sharing-economy*' or displacing physical goods by digital goods are promising. The same applies for closed-loop material cycles, recycling systems and intelligent waste avoidance and treatment. These concepts are perfectly applicable to foster learning and behavioural changes on the supply and the demand side. The core idea of Neo-Schumpeterian Economics, however, is the *supply of and demand for* new technological solutions within a comprehensive economic transformation process (Geels 2002),

i.e. different goods and services are produced and demanded in different, namely sustainable ways. Exploring and exploiting the technological possibilities of the bioeconomy not only creates new investment opportunities but is also the condition-sine-qua-non for the required socio-economic and cultural changes. The consumers' acceptance of bio-based products and their demand are indispensable for a successful transformation. Innovations and changed consumer attitudes are complementary conditions for the creation of a sustainable production system.

Change can be either of an incremental type in terms of small improvements step-by-step along well-known technological trajectories or it can be fundamental, leading to structural changes and the emergence of new and the disappearance of old industries. To simplify, we assume in this chapter that incremental technological changes are based on existing technological solutions, whereas radical technological changes question major existing production processes. They might lead to massive upheaval in the global production system in the sense of *creative destruction* (Schumpeter 1943).

Incremental innovations make relatively small, step-wise changes to existing goods and services. They typically follow well-known technological trajectories and retain the basic design of the good or service.

Radical innovations are changes that reshape designs, knowledge, processes or even market structures.

Creative destruction describes the process through which novel innovations replace and make obsolete previous innovations.

Because this chapter deals with the fundamental transformation of current production systems, radical technological innovations are in the spotlight, which encompass the overcoming of the lock-in situation in fossil fuels (Unruh 2000) and the establishment of a knowledge-based bioeconomy (Pyka 2017; Pyka and Buchmann 2016). Without doubt, this transformation process is radical, qualitative and long-term. It was already in *Business Cycles*, published in 1939, when Schumpeter revitalized Kondratieff's Theory of *long waves* in order to explain such processes as regular processes in long-term economic development. His illustration of the discontinuous nature of economic development is famous: "Add successively as many mail coaches as you please, you will never get a railway thereby" (Schumpeter 1934, p. 64). So far, the literature highlights five long waves: The beginning industrialization around the year 1800 represented the first long wave and was fuelled by the steam engine and by cotton processing. Then, starting around the year 1850, the widespread availability of steel and the diffusion of railways constituted a second long wave. Again, in the early twentieth century, this Kondratieff cycle was replaced by electricity and chemicals. In the post-war period, the third long wave gained momentum by mass production and the automobile as well as the petrochemical industries. Since then, manufacturing activities built on oil as a second fossil fuel apart from coal. From the 1980s, one refers to the fifth long wave, which is reflected in the fast and ubiquitous diffusion and application of information and communication technology. Now, at the beginning of the twenty-first century, another paradigmatic change is in the air, being characterized, however, by one major difference to previous situations of radical change. Whereas previous cycles were driven by technological bottlenecks and their overcoming, in the twenty-first century, we face the vital question of how to restore environmental sustainability of economic activities. The knowledge-based bioeconomy plays a key role in this transformation process which, of course, like previous radical changes still is confronted by fundamental uncertainty (Knight 1921).

The literature provides many alternative terms for the massive change, shaking global production systems: Freeman (1991) and Dosi (1982) call them techno-economic paradigm changes, Sahal (1985) uses cartographic analogies and refers to technological guideposts

that are pointing to technological avenues. All authors highlight the confrontation with profound changes that economic systems are faced with over longer periods of time, which question all established production approaches. Not a single technology is responsible for this phenomenon, but several complementary developments that include, apart from a package of mutually dependent technologies (e.g., combustion engine, petrochemistry, assembly line production), numerous infrastructural developments (e.g., road structure, filling station network), behavioural changes (e.g., suburbs and commuter flow, shopping malls outside the city centres) as well as institutional changes (e.g., spatial planning and commuter allowance, etc.). The old paradigm will not be replaced by the new one until all these elements interact.

The Neo-Schumpeterian approach provides us with crucial hints on the process of the forthcoming change. For this purpose, we discuss in the following section how innovations are supported by the discovery and successful diffusion of new knowledge. Knowledge-based economies organize innovation systems composed of different actors that establish a creative environment for mutual learning and knowledge creation. No innovation would have ever been established if it had not attracted consumers' interest and if it had not been leveraged by their purchasing power. We will focus on these questions in section three. Knowledge-based societies consider new concepts in the sense of *responsible innovation* that are decisive in bringing an entire economy on a new sustainable path, shaping growth and development. Section four deals with the massive economic impacts originating from these technological and knowledge-driven changes. It requires, besides technological change, also institutional change in a co-evolutionary fashion, if new sustainable technologies are to achieve the aspired transformation of the economic system.

32.2 Innovation Systems and Knowledge

Neo-Schumpeterian scholars (e.g., Dosi et al. 1988; Lundvall 1992, 1998; Nelson 1993) strongly emphasize the systemic character of innovation processes. So-called *innovation systems* are composed of different actors (companies, research institutions, political actors, consumers, etc.) and linkages between these actors (flows of goods, R&D cooperation, knowledge transfer relationships, user–producer relationships, etc.). These linkages are required to ensure mutual learning and common knowledge development to solve complex innovation challenges. Such systems are characterized by their dynamic and co-evolutionary nature and are thus enormously complex, as both, actors and their knowledge, along with linkages and interactions between them, may change over time.

Excursus 9.1 Innovation Systems

The concept of innovation systems dates back to the mid 1980s but is still a popular approach to analyse aggregate innovation activities. An innovation system is a system of heterogenous actors, i.e. firms, education organisations, research organisations, government, etc. that are connected by various types of links and interactions and jointly cooperate in generating, accumulating and diffusing knowledge, competences and artifacts.

The aim of an innovation system is to facilitate the development, diffusion and utilisation of innovations and new technologies. Within an innovation system, activities are not centrally orchestrated, and actors do not necessarily pursue the same objective and employ the same approaches. Innovation is thus an emergent phenomenon created under certain conditions by the interaction of heterogeneous actors. The dynamic of an innovation system is driven by the tension and conflicts created by the heterogeneity of motives, objectives and approaches, the development of heterogeneous solutions as well as market selection that works on the level of technologies, products and firms.

Dosi (1982) takes this systemic conception as a starting point in defining technological paradigms as "[…] set of procedures, or a definition of the 'relevant' problems and of the specific knowledge related to their solution". Transferred to the knowledge-based bioeconomy, the core idea is substitution, i.e. replacing carbon-based materials and energy with bio-based materials and energy. This can only be achieved by applying a variety of technological processes in the entire breadth and depth of the value-added chain. In this process, the exploration of economic complementarities in terms of cross-fertilization of different knowledge fields matters. For example, to a large extent, digitalization allows for an extension of value chains by increasing the added value in new sustainable production sectors in a CO_2-neutral way (e.g., by electric mobility based on renewables and by establishing so-called smart grids, etc.). The concept of technological paradigms also illustrates that a paradigm shift is not possible at any time. A *window of opportunity* will only occasionally be opened and allow for a paradigm shift when several interconnected technologies are established, and the creation of conducive demand-side and institutional conditions happens simultaneously. This, of course, also holds for the emergence of a new bioeconomic innovation system and requires a sound balance of the various actors and their activities. For this reason, we introduce the notion of a *dedicated innovation system*.

The theory of industrial life cycles, which emphasizes the strong dynamics in the emergence and decline of industries, gives a first hint on the meaning of the development of a dedicated innovation system supporting the transformation towards a knowledge-based bioeconomy. Typically, industrial development is divided into four stages:

1. A development phase (new knowledge creates prerequisites for innovation)
2. An entrepreneurial and growth phase (many market entries of smaller innovative firms)
3. A saturation and consolidation phase (formation of industrial standards, mergers and acquisitions as well as market exits)
4. A downturn phase (oligopolistic competition in only less innovative industries) (e.g., Audretsch and Feldman 1996)

Although the bioeconomy does not represent a well-defined industrial sector, understanding the theory of industrial life cycles is of crucial importance to govern the transformation process towards the knowledge-based bioeconomy. Without doubt, the bioeconomy has to be characterized as cross-sectional. On the one hand, several new sectors will emerge, e.g. in the fields of bioplastic, waste management, or biorefineries. On the other hand, already existing sectors in the fields of vehicle construction, battery technology, pharmaceuticals, etc., will gain new momentum by the arrival of bioeconomic approaches. Therefore, we argue that new sectors will emerge by establishing bioeconomic technologies, and development dynamics of some already existing industries will receive new impetus at the same time. Adjustments of old and development of new institutions (e.g., in Germany the Renewable Energy Act, the Greenhouse Gas Emissions Trading Law, etc.), adjustments of consumer habits and the emergence of new educational opportunities in terms of co-evolution will accompany these processes and establish the institutional, the industrial and the consumer pillars of a dedicated innovation system.

The patterns and nature of new businesses in the bioeconomy are thus strongly influenced by national institutions and organizations (Casper et al. 1999; Whitley 1999). Institutions are defined as "a set of rules, formal or informal, that actors generally follow, whether for normative, cognitive, or material reasons" (Hall and Soskice 2001). And organizations are "durable entities with formally recognized members, whose rules also contribute to the institutions of the political economy" (North 1990, Hall and Soskice 2001). In this interplay between organizations and institutions, the knowledge base of an economy is created by the education and research system and represents one of the most important prerequisites for the transformation towards a bio-economic production system (Geels 2002). This automatically

relates to a high level of uncertainty in particular concerning the required future competences. In this complex process, numerous individual knowledge fields are potentially relevant for the transformation and are already identified, e.g., synthetic chemistry, process engineering, genetic engineering, food technology or informatics. It is decisive to understand the dynamics of these knowledge fields and the possibilities of their recombination with other knowledge fields and adequate actors in order to create an innovation system. In many cases, linkages of different knowledge fields (*cross-fertilization*) are responsible for the emergence of extensive technological opportunities: for instance, a completely new industry, bioinformatics, has been initiated by the fusion of two so far unrelated knowledge fields: database technology and molecular biology. Because linking different knowledge fields is highly uncertain, private actors might not start, and governmental innovation policies matter. Knowledge about future potentials, therefore, is essential for supporting research and innovation policies: the analysis of knowledge and network dynamics allows for the identification of development trajectories showing sectors requiring public attention and support concerning research and development in order to close existing knowledge gaps and build bridges between various knowledge domains (Burt 2004; Zaheer and Bell 2005).

32.3 Innovation in Knowledge-Based Societies

It has already been mentioned that also consumer knowledge plays an important role in the development and establishment of sustainable consumption patterns in a knowledge-based bioeconomy (Geels 2002). Therefore, the analysis of the transformation process has to include the interaction of technological development, demand and acceptance of innovative solutions as well as sociological variables. The latter includes education, age, income and gender. All are important explanatory factors determining attention and readiness to deal with bioeconomic issues. A bioeconomic innovation will only be successful when consumers accept it. The direction of the transformation process is, comparable to the importance of the policy realm, determined by consumers, i.e. an important question has to address consumers´ openness to the bioeconomy and its products.

Finally, (real and virtual) social networks matter for the establishment of new consumption patterns. They can contribute significantly to a diffusion of consumers' behavioural patterns and values (Robertson et al. 1996; Valente 1996; Nyblom et al. 2003; Deffuant et al. 2005). Recent studies show that attitudes are substantial for the development of social relationships and that, in turn, social relationships considerably influence behaviour and attitudes. In the field of renewable energies, for example, the initiative of municipal utilities' customers has led in many cases to a 'green' orientation of regional power supply. In some cases, citizens' networks finally transformed to investment companies that are engaged in wind farms.

Critical issues are to be dealt with in democratic processes in order to be widely accepted. Not everything that is technically possible is also socially desirable. In the field of the bioeconomy, this may, for instance, include the use of genetically modified organisms in agriculture. In fact, these organisms promise efficiency advantages with regard to the consumption of land and water, but their long-term health and environmental risks cannot be completely (as with any new technology) anticipated. Accordingly, technological developments require consumers' acceptance and thus depend on the level of education in an economy. This raises the question of a society's openness towards innovations that are fundamentally associated with uncertainty. The concept of *Responsible Innovation* summarizes the future-oriented organization of development and is currently discussed with a high priority by European policy makers and institutions. A comprehensive working definition has been developed by von Schomberg (2011). He describes responsible innovation as "a transparent, interactive process by which societal actors and innovators become mutually responsive to each

other with a view to the (ethical) acceptability, sustainability and societal desirability of the innovation process and its marketable products (in order to allow a proper embedding of scientific and technological advances in our society)" This means that innovations are not exclusively evaluated by their economic efficiency, but different aspects (e.g., consumer protection or ecological aspects, see Schlaile et al. 2017) also matter and are to be evaluated. Discussions on biofuels (*fuel vs. food*) show that both, a pure economic and a one-dimensional ethical perspective are not sufficient. The quality of these discussions depends on the discussants' mutual understanding, which in turn depends on the participants' level of knowledge.

Modern plant breeding and production of seeds are bioeconomy fields of innovation in which issues of responsibility are discussed frequently and controversially. German consumers are sceptical about interference with the genome of food crops, but individual points of criticism remain unclear. New breeding techniques introduced, e.g., *Genome Editing,* enable scientists to selectively modify DNA strands of crop plants. These techniques are considered innovative as they may allow breeding of potentially efficient plants in fast and cheap ways. Species developed this way hardly differ from those of conventional breeding. The Central Advisory Committee for Biological Safety does not classify these techniques as genetic engineering, especially because no new combinations of genetic material are made. As the Genetic Engineering Act does not explicitly address these techniques, legal clarification is still necessary as to whether these techniques are classified as genetic engineering at all. Dissemination potential and acceptance are influenced by this result. Here again, the necessity to include education and information policies becomes evident to support the transformation towards a knowledge-based bioeconomy.

The concept of s*ocial innovation* (e.g., Hanusch and Pyka 2013) emphasizes the importance of active citizenship in innovation. Thus, according to the understanding of the European Commission, this term includes innovations that are social, both in relation to their objective and their instruments. In particular, this includes innovations referring to the development and the application of new ideas (for products, services and models), covering at the same time social demand and creating new social relationships or collaborations. The whole society should benefit and contribute to generate new impetus for improvement. Social innovations can make a major contribution to rural development and promote economic resilience in these regions by strengthening cooperative behaviour. Rural cooperatives (e.g., regional producer and marketing associations, winegrowers' cooperatives, tourism associations, etc.) can help to develop regional competitiveness considering ecological and social aspects. As a consequence, within the framework of a bioeconomy, rural regions that are notably affected by the already imminent demographic change and subsequent depopulation receive new opportunities for economic development.

32.4 The Economics of Change

The sections above illustrate that a transformation of the prevailing economic system towards a bioeconomy is an extremely complex process. Various actors participating in different roles are contributing different pieces of knowledge. In this process, innovative adjustments in already existing industries as well as the emergence of new and the disappearance of mature industries can be observed simultaneously. In addition to the substitutive relations of new bio-based industries to traditional oil-based industries, there are numerous essential complementary relations giving further momentum for the transformation process. First and foremost, there are the possibilities and application fields of digitalization. Digitalization allows to replace many oil-based products and energy-intensive services simply by bits and bytes. Simultaneously, digitalization offers a wide range of opportunities by coordinating decentralized and very detailed bioeconomic technologies and processes such as energy production and distribution. This affects the composition of individual sectors where a coexistence of

large, diversified companies and small highly specialized technology companies is a likely solution. Finally, digitalization also offers consumer platforms to efficiently organize *sharing economy* approaches. Finally, successful knowledge generation and diffusion of relevant bio-economic knowledge depends on dynamic innovation networks (Pyka 2002) in which different actors jointly share and create new knowledge. The consumers, represented, for example, by consumer associations or politics, will play a key role in these innovation networks and will help to establish networks in early stages of technology development.

In a knowledge-based bioeconomy, investment and economic growth still represent a crucial element for employment, international competitiveness and income generation. The bioeconomy can make important contributions to accelerate investments by providing new investment opportunities generated by fundamental innovations and thereby bringing currently available large quantities of liquidity to a productive use. This, in turn, accelerates the technological paradigm shift (Perez 2010).

The time path of the transformation process represents another critical component and has been explored only partially so far. On the one hand, it is high time to reduce carbon-based production methods. On the other hand, there will be frictions in the transformation process being caused, for example, by a lack of specialists and required competences. In this context, the so-called *sailing ship effects* (Howells 2002), frequently observed with radical innovations could be made good use of. In the middle of the nineteenth century, when the existence of the established sailing ship technology was threatened by the arrival of new steam ships, shipbuilders – not having changed their technologies for many decades, if not centuries – began to innovate again. Due to the threat of innovative technologies, adjustment reactions in predecessor technologies can be observed with the aim to prevent the ancient technologies to be quickly replaced. Such adjustment reactions are, for example, fuel-efficient combustion engines and hybrid technologies as a reaction to the emergence of electric vehicles. These adjustments are advantageous since they pursue the same environmental objectives (e.g., inner-city fine dust and noise reduction, etc.) and thus provide more time to develop new technologies. Accordingly, the transformation process will for longer periods of time feature a co-existence of traditional and bio-based industries. Furthermore, it will be important to concurrently steer the relevant innovation processes in traditional technologies. This co-existence further increases complexity. At the same time, innovation policy is given room for manoeuvre and yet insufficiently developed technologies are prevented from being introduced prematurely, which might cause promising approaches to fail.

Distributional effects of the transformation process are important for social acceptance. A bio-based economy on an industrial scale will largely represent a knowledge-based economy. Consequently, additional demand for high-skilled workers arises, whereas opportunities for low-skilled workers decrease. This means a potential loss of jobs for less-skilled workers in traditional industrial production. But apart from that, there will be demand for different goods and services whose compensation potential with regard to added value and employment is still unclear. Moreover, it remains open to what extent companies are prepared for this transformation into the bioeconomy. Transformation processes will lead to a devaluation of competences so far responsible for economic success. How do established companies deal with the so-called *not-invented-here-syndrome*, overcome operational blindness and shape transformation processes actively in order to obtain added value at their established locations?

From this follows that distributional effects have an important regional dimension: does the bioeconomy strengthen divergence processes between regions or does it help to achieve more convergence? The approach of creating networks in the sense of the so-called *smart specialization principle* (Foray et al. 2009) connecting regional strengths along value-added chains in the best possible way is promising but only sparsely implemented so far. Thus, in general, polarization tendencies

leading to economic as well as political and cultural concentration of power and resulting in strong centre–periphery structures can be avoided. But it still remains unclear, how strong and operational meaningful politically induced networks are in comparison to self-organized networks and how policy might exert influence. First findings indicate signs of a potential disintegration of the networks when political support is withdrawn (Green et al. 2013).

Transformation towards a knowledge-based bio-economic production system is supposed to terminate the existing negative relations between economic growth and environmental pollution, use of resources, climate change and energy consumption, and to promote a sustainable economy. The following questions are closely linked to the basic uncertainty of innovation and cannot be answered ex ante: 'which contributions are to be made by individual sectors?', 'what complex feedback for national and international competitiveness are to be expected?' and 'do so-called *rebound effects* possibly reduce or even overcompensate the positive effects of the transformation? Institutional rules, such as a self-commitment of oil-producing countries to reduce their outputs due to the declining demand caused by bio-economics, are a way to reduce these uncertainties, at least partly. It remains necessary for the leading actors, companies, households and policymakers to refrain from optimization approaches and profit maximization in this transformation process. The complexity and uncertainty of this process require the awareness of all actors to experimental behaviour (*trial-and-error*), which always also includes the possibility of failure.

32.5 Conclusions

Socio-economic systems have been exposed to permanent transformation processes since the industrial revolution. While development processes so far have been driven 'only' by result-oriented innovation processes, the character of the bio-economic transformation process is clearly concretized by society and politics. In the past, mainly bottlenecks caused by scientific-technological restrictions were overcome by vast technological revolutions, shifting the socio-economic system on new trajectories without giving direct instructions to the direction of the development process. At the beginning of the twenty-first century, however, the massive accumulation of greenhouse gases in the atmosphere since the beginning of the industrial revolution and the vulnerability of our present ecosystems reveal that global thresholds are almost surpassed. Thus, the level of freedom for future developments is restricted in order not to irreversibly damage natural conditions for human life and biodiversity. It is yet unclear whether this transformation process succeeds in the desired way and how it can be governed by political influence to achieve existential objectives of the global human society.

New technological developments alone are not enough to transform the socio-economic system. In a first step, they only create the necessary potential for radical changes affecting the economy as a whole. Converging trajectories and synergies that may finally introduce the paradigm shift necessarily require a broad social consensus on a specific use of these technologies. This means an initiation of a direction of development which connects investment decisions, innovations and the tackling of basic uncertainty by politics (Pérez 2013). The 'green growth paradigm' based on bio-based technologies can be such a direction, bringing together the potential of different technological developments and exploring their full potential. This requires political decisions supporting a new orientation of research and innovation activities, exploitation of new energy sources, improvements in productivity of natural resources and new sustainable ways of living and producing (Pérez 2013). Moreover, in such a transformation process, catching-up economies have to be provided with new opportunities for economic development without overstretching global natural resources and environment. Thus, a political and social direction is essential for a successful transformation process (Mazzucato and Perez 2015).

Examples include the development of new products within emerging bio-economic inno-

vation systems. In this perspective, innovations require an interplay of actors along value-added chains, which might lead to the development of new industries. In the past, for example, the provision of cheap electricity led to the spread of fridges and freezers in private households, which brought innovations in the fields of frozen food and packaging. Similarly, the creation of a *Sharing Economy* may lead to new digital coordination platforms and the creation of sustainable designs by product manufacturers in the bioeconomy. *Planned obsolescence*, a phenomenon wasting resources and shortening product life cycles, would be eliminated this way and new sectors, for example, in the field of repair and maintenance services are initiated. Important determinants shaping long-term development are networks and clusters. They help to reduce uncertainty and support self-reinforcing effects. Furthermore, social changes and changing lifestyles are both an expression and a driver of this transformation process (Mazzucato and Perez 2015).

Therefore, the role of governments is not only restricted to the correction of market failures. In fact, by ensuring investment safety and reducing risks and uncertainty, government instruments prepare for the emergence and flourishing of new markets (Mowery et al. 2010). A crucial task for policies in the realm of innovation and entrepreneurship is the transition from invention to innovation, i.e. the expansion of bio-economical activities in a market. Correspondingly, a growth path based on bio-economics is more than a mere replacement of crude oil by renewable resources or renewable energies. It rather needs a *dedicated innovation system* creating synergies, knowledge transfer and networks between manufacturers, suppliers and consumers. It requires a comprehensive reorganization that includes the entire economy and renews production and consumption patterns in their present forms, which were shaped by previous transformation process within the oil-based paradigm.

The technological potential of a bioeconomy is a necessary but insufficient condition for this transformation process. It also requires democratic consensus on the broad development and wide application of this technological potential. This includes the exploration of new trajectories and the fusion of new and existing technological trajectories. Markets in which innovations are profitable do not arise on their own but rather need feedback loops between political decisions, corporate strategies and consumer preferences.

Do you want to learn more about innovation in the bioeconomy? Take a look at Supplementary Video 32.1, a video from our MOOC "Concepts of Sustainable Bioeconomy" (2021).

Questions

1. Discuss the likely social, economic and environmental effects of the sharing economy. Put particular emphasis on the rebound effect that could emerge in this context due to the fact that the sharing economy makes the use of resources for individuals cheaper. How can policymakers counter this rebound effect?
2. What does *creative destruction* mean? Provide two historical examples, where creative destruction has played a particularly important role.
3. What is the Kondratieff-cycles and what are the inventions that are associated with them?
4. Sketch the i) mutually dependent technologies, ii) infrastructural developments, iii) behavioural changes and iv) institutional changes that you expect to be necessary in the transformation towards a knowledge-based bioeconomy.
5. What is a *dedicated innovation system* and how could it look like in case of the transformation towards a bio-based economy?
6. Describe the term *Responsible Innovation* and discuss its meaning in the context of Genome Editing

Answers

1. The sharing economy reduces costs per user by enabling shared resource use, potentially increasing resource effi-

ciency. If the sharing economy is an expression of a new more sustainable lifestyle, no rebound effects are to be expected. Policy measures to support sharing approaches and the emergence of new lifestyles:
   (a) Taxation, to discourage environmentally harmful behaviour.
   (b) Regulations, to prioritize resource efficiency.
   (c) Educational initiatives, to raise awareness of sustainable practices and to change consumer preferences (*learning*).
2. *Creative destruction* refers to the process in which new technologies replace old ones, leading to the decline of existing industries and jobs. Examples:
   (a) The introduction of the automobile led to the decline of the horse-and-carriage industry.
   (b) Digitalization replaced traditional newspapers with online media.
3. Kondratieff cycles are long-term economic waves driven by foundational innovations. Examples include:
   (a) 1st Cycle: Steam power.
   (b) 2nd Cycle: Electricity.
4. Necessary developments for a transformation toward a knowledge-based bioeconomy include:
   (a) Technologies: Efficient biomass processing methods.
   (b) Infrastructure: Networks for bio-based products.
   (c) Behavioural Changes: Awareness of sustainable consumption habits.
   (d) Institutional Changes: Adjusting policies to support innovation.
5. A dedicated innovation system is a purpose-built network of actors supporting the development and adoption of new technologies. For a bio-based economy, it could include research centres, funding programmes and public–private partnerships. The dedication includes besides the sustainability orientation a strong entrepreneurial orientation.
6. *Responsible innovation* emphasizes ethical, ecological, and societal considerations in technology development. In the context of genome editing, this might involve stringent regulations and public engagement in decision-making processes.

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Inclusive Innovation in the Bioeconomy

Lotte Asveld



Fig. 33.0 Inclusive innovation in the bioeconomy. (© Ricardo Vargas-Carpintero) (► https://doi.org/10.1007/000-hve)

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The bioeconomy offers a vision of economic prosperity and ecological sustainability by substituting fossil resources with biomass. The use of biomass is essential to achieve global sustainability targets and novel technologies emerge to exploit biomass in increasingly efficient ways. However, these technological advancements raise critical questions about economic and environmental justice, including the distribution of benefits, ownership rights and their impact on global inequalities. Particularly, concerns arise about the sourcing of biomass from the Global South for processing in the Global North, and how these practices affect sustainability and biodiversity. This chapter explores the concept of inclusive innovation as a solution to these uncertainties, emphasising the engagement of diverse stakeholders in the design and development of technologies to enhance their legitimacy and acceptance. Inclusive innovation aims to improve the livelihoods of the most vulnerable by integrating their perspectives into innovation strategies. Environmental justice, focusing on distribution, processes, recognition and capabilities, is essential for achieving fair and sustainable bioeconomic practices. By applying these concepts to both regional and global value chains, this chapter demonstrates how meaningful inclusion can enhance opportunities for disadvantaged groups and align bioeconomic practices with local capacities. Inclusive design can also generate support among European farmers to deliver to bio-based value chains. Ultimately, embracing inclusive innovation and environmental justice ensures that the bioeconomy fosters equitable and sustainable development for all.

Learning Objectives

After studying this chapter, you will…

- …be able to explain the concepts of inclusive innovation and environmental justice (see ► Sects. 33.2 and 33.3).
- …be able to explain why these concepts are relevant to the bioeconomy (see ► Sects. 33.2, 33.3, and 33.6).
- …be able to illustrate this relevance with examples from current practices around the use of biomass (see ► Sect. 33.6).

33.1 Introduction

The bioeconomy is an appealing concept that integrates the promise of economic prosperity with that of ecological stability by replacing fossil resources with biomass. Recent advances in bioengineering, such as CRISPR-Cas and synthetic biology approaches, offer novel pathways to modify microorganisms into high-performing production platforms for a wide range of products (Straathof et al. 2019). Novel bioprocessing technologies increase the efficiency of using biomass, which is essential to meet the global energy demand in a sustainable manner (Alazaiza et al. 2024).

Such increasingly advanced technologies give rise to questions about economic and environmental justice: Who will benefit from these sophisticated technologies? Who will own and distribute them? How will they affect global economic inequalities, especially considering the fact that a lot of the biomass will be sourced from the global south and processed in the global north (Lühmann 2021)? And how can they contribute to sustainability?

These questions emerge against a background of multifaceted uncertainties. As explained in ► Chap. 1, Biomass encompasses a wide range of feedstock including plants, trees, algae, marine organisms, microorganisms and animals. Each of these feedstocks emerges from its own societal context, in which specific challenges may complicate the quest to arrive at sustainable products. Crops are grown in various agricultural practices, each of which has its own unique set of circumstances. Furthermore, the collection of residues from various areas is impacted by local infrastructures or local social structures. Often changes may be required in existing agricultural practices to achieve an efficient and sustainable sourcing of biomass (Robaey et al. 2022).

Additionally, it may not always be clear what the most sustainable approach is with regard to the utilisation of feedstocks. Is it always more sustainable to use residues, or is it sometimes more efficient to use dedicated energy crops? Does the use of novel

technologies lead to more sustainable farming practices or does it undermine traditional practices that are actually more sustainable? All these questions require dedicated approaches to deal with them.

In this chapter, we will discuss the concept of inclusive innovation as a way to manage these uncertainties, while at the same time addressing economic and environmental justice (Asveld 2021). We will explain these concepts in more detail and show how they are relevant to current developments in the bioeconomy.

33.2 Inclusive Innovation

The concept of inclusion has garnered attention as a crucial element of Responsible Research and Innovation (RRI). It emphasises engaging a diverse range of voices in developing new technologies to enhance both the legitimacy and acceptance of innovations (Stilgoe et al. 2013). This approach shifts away from an innovation system dominated by technological experts. Inclusion, in this context, is viewed primarily as a process where multiple stakeholders provide input on the desirability of a specific innovation's design. Such inclusion is generally seen as essential for achieving societally desirable outcomes.

Some authors, however, emphasise inclusion as an outcome of innovation rather than just a prerequisite. In the bioeconomy context, inclusive innovation is described as a "new way of doing things that may improve the lives of the most needy" (Bryden et al. 2017). Here, the actual benefits of an innovation are central. This focus on enhancing the livelihoods of the most vulnerable is also evident in the approaches of inclusive agricultural value chains (Devaux et al. 2018) and inclusive innovation for development in general (Heeks et al. 2014). These approaches demonstrate a progression from merely providing products tailored to the most needy (e.g., frugal innovation) to more comprehensive strategies that consider the living conditions and overall well-being of vulnerable groups (Ros-Tonen et al. 2019).

Broadly, inclusive innovation aims to expand both the target audience of an innovation, and the range of stakeholders involved in its development and design. The focus can be on the product design itself, incorporating various stakeholders' perceptions to create a more inclusive design or taking a comprehensive approach that also considers the local context of production (Asveld 2021).

> ***Inclusive innovation*** aims to broaden both the target audience as well as the stakeholders involved in the development and design of an innovation, through tailored design, inclusion of diverse perspectives or a comprehensive design approach that encompasses the local context of all stakeholders involved.

Involving local producers or potential users offers both moral and epistemic benefits. This implies that inclusion can provide a basis to increase knowledge as well as legitimacy. Engaging local stakeholders in bio-based production systems can address numerous uncertainties (Rist et al. 2007). Local producers often possess valuable knowledge about land management, their natural environment and related biomass (Šūmane et al. 2018). While inclusion can lead to more sustainable bio-based products and value chains, it also promotes environmental justice, which will be discussed in more detail below.

33.3 Environmental Justice

Environmental justice plays a crucial role in any technological development related to sustainability, particularly within the bioeconomy. This concept can be broken down into four key elements: distribution, processes, recognition, and capabilities (Schlosberg 2007). Each of these aspects is integral to the bioeconomy, as we will explore below.

Distributive justice involves the equitable allocation of burdens and benefits within society (Lamont 2017), closely aligning with eco-

nomic justice. For simplicity, we will treat these concepts interchangeably. Economic incentives designed to promote the bioeconomy often disproportionately benefit established agribusinesses or urban consumers (Bastos Lima 2022). Meanwhile, the burdens, such as monoculture expansion and environmental risks, are primarily borne by resource-poor rural populations (Bastos Lima 2022). Furthermore, smallholders frequently struggle to integrate into and reap the benefits of global bio-based value chains (Balkema and Pols 2015; Robaey et al. 2022). In the bioeconomy, distributive justice necessitates prioritising the needs of vulnerable local stakeholders and ensuring a fair distribution of environmental, economic and social risks (Gupta and Lebel 2020).

While distributive justice focuses on how impacts are allocated, recognition justice addresses the unique needs and potential harms facing vulnerable groups (Dillman and Heinonen 2022). This aspect emphasises acknowledging the social, cultural, historical and economic structures that underlie unequal distributions (Velasco-Herrejon and Bauwens 2020). Relevant questions include who is affected and which sections of society are under- or misrepresented. Ignoring the concerns, views and needs of vulnerable stakeholders affects both distributive and procedural justice, as these communities are often excluded from bioeconomy governance and the benefits of expanded bio-based production (Bastos Lima 2022). Implementing environmental justice in the bioeconomy should begin with recognising these stakeholders and their perspectives on rural development.

In addition to distributive and recognition justice, it is essential to examine the processes that lead to fair or unfair distributions (Velasco-Herrejon and Bauwens 2020). Procedural justice pertains to participation in the design process and decision-making about future directions (Bastos Lima 2022). In developing the bioeconomy, it is vital to consider who is involved in decision-making and how these decisions are made. By including local stakeholders in these processes, their knowledge is mobilised, potentially leading to alternative designs and viewpoints that better reflect specific needs and circumstances. Beyond justice claims, involving local stakeholders can also enhance the effectiveness and sustainability of bio-based products and value chains, as producers often possess valuable knowledge of land management and cultivation practices (Asveld et al. 2023).

Any inclusive and just approach to the bioeconomy must consider the disparities in skills and knowledge among individuals, as well as economic, social and institutional inequalities. It must also account for the diverse cultural contexts and norms that influence global value chains and shape individuals' opportunities (Alsop and Heinsohn 2005). The concept of capabilities is helpful here, as it identifies the distribution of opportunities among various actors. These opportunities represent more structural elements of inclusion compared to narrower indicators like increased income or improved sanitation (Oxoby 2009).

The capability approach emphasises individual human capabilities, or "a person's real freedoms or opportunities" (Robeyns 2017) to achieve what they value. Examples include the capability to become educated, live a healthy life and grow one's own food (Nussbaum 2000). The availability of these capabilities depends on a range of interconnected inputs, such as institutions, public goods, social practices, resources and skills, collectively known as "conversion factors" (Robeyns 2005). When people exercise their agency, they make choices about which capabilities to develop into "functionings" (states or activities that create well-being, such as getting educated or living a healthy life). Thus, capabilities represent options not outcomes.

Environmental justice refers to the equitable distribution of environmental benefits and burdens, inclusive decision-making processes, recognition of the unique needs of vulnerable groups, and the enhancement of individuals' capabilities. It aims to address and rectify the social, cultural, historical, and economic inequalities that impact on how environmental resources and risks are shared within society.

33.4 Environmental Justice and Inclusion in the Bioecononomy: Global and Regional Value Chains

In this section, we will apply the aforementioned concepts to a central element of the bioeconomy: namely global and regional value chains. Bio-based value chains often build on biomass derived from a biomass-rich region, from where it is exported to a technology-intensive region, sometimes after pre-processing at the site of production. The raw or pre-processed biomass is processed further into a chemical product, for example, base chemicals or fuels or products such as plastics or bio-based lubricants. As discussed above, inclusion of biomass producers in the set-up of value chains can be beneficial for both moral and epistemic reasons. However, many biomass producers are located in the *Global South*, where conditions for inclusion can be suboptimal, for instance, because of weak institutions (Postal et al. 2020; De Gelder and Asveld 2024).

> ***The Global South*** refers to countries that are usually considered as 'less developed', which is often due to colonialisation and its continuing impact.

Additionally, cultural values and practices between producers and other actors in agricultural (and bio-based) value chains may vary widely (Ros-Tonen et al. 2019), as may access to resources (Devaux et al. 2018). Historically, these differences have not always been well addressed in the setting up of bio-based value chains, and this has contributed to their failure (Romijn and Caniëls 2011) or created new economic dependencies, making local biomass producers more vulnerable (Bottazzi et al. 2018).

For meaningful inclusion, opportunities for local actors should be central to the set-up of the value chain. For this, enabling the involvement of local actors and values at the start of new value chain development projects is essential (Palmeros Parada et al. 2020, 2021). Inclusion should revolve around increasing opportunities for those least well off (Bryden et al. 2017). Increased opportunities not only provide individuals with the option to shape their lives as they see fit by reducing stifling economic dependencies but also allow for diversity and human flourishing, which is what inclusion should be about. At the same time, the value chain should be designed in alignment with existing local capacities and resources, such as skills and knowledge, to increase its chance of operating effectively and successfully.

The capability approach offers a lens to tailor value chains to the skills, knowledge and preferences of local stakeholders. This contributes to all aspects of environmental justice because it leads to more equal distribution of benefits, to recognition of the views of all stakeholders and to procedural justice because it takes these views into account while also considering the diversity in the capability to participate in decision-making.

This may result, for instance, in a value chain that starts from the relatively small plots of coffee producers in Colombia instead of opting for a more centralised version in which these small plots are concentrated into one bigger plot. By respecting the ownership of farmers of their small plots, and hence collecting residues from each of them individually, their capability of controlling their environment is acknowledged and maintained (Van der Veen et al. 2024).

Developing value chains based on local capabilities requires a nuanced approach. While aligning technologies with existing skills—such as designing a hand bike for individuals with paralyzed legs—is logical, the broader goal of inclusion entails creating opportunities for people to expand their capabilities. This raises a critical question: Should we design technologies to match current capabilities, such as existing levels of education, by using relatively simple solutions? Or should we aim for future, desirable capabilities, such as access to higher education and the development of advanced technological skills? These future capabilities could arise through

increased income and inclusion in global value chains.

For example, while a hand bike directly enhances mobility opportunities for someone with paralyzed legs, the technological choices in bio-based value chains offer a broader spectrum of possibilities, either by adapting to current skills or fostering future growth. Addressing this dilemma requires diverse strategies. Three overlapping, complementary approaches for designing inclusive bio-based value chains can be applied (see Asveld et al. 2023 for a further elaboration and discussion of these strategies and the case-study):

1. Design for existing capabilities.
2. Provide adaptive designs to foster new capabilities.
3. Invest in enabling conditions for novel capabilities.

Integrating these strategies allows for the accommodation of both existing and evolving capabilities.

Excursus 33.1 Case Study: Jamaican Sugar Cane Farmers

Many Jamaican farmers seek to diversify their income sources. One potential avenue is selling sugar cane to bio-based value chains for biofuel production. When designing such a value chain, how can the farmers' current financial needs and existing conversion factors be considered?

1. **Respecting Existing Practices**
   One approach is to retain sugar cane as the primary feedstock, even if alternative crops might yield higher returns. This decision allows farmers to build on their existing practices, respecting local traditions and social norms while minimising the need for new, unfamiliar practices.
2. **Leveraging Established Technologies**
   Ethanol production from sugar cane is a globally established process. By choosing ethanol as the main product, Jamaican farmers and industry actors can adopt proven practices already in use elsewhere. This approach aligns with the conservative stance of many stakeholders in Jamaica's long-established sugar cane industry, which dates back to colonial times. Utilising familiar practices and technologies ensures a smoother transition and offers a stable opportunity to diversify income.
3. **Integrating Advanced Bagasse-to-Energy Solutions**
   Bagasse, a byproduct of sugar cane processing, can be converted into energy. While current machinery in Jamaica is outdated, introducing modern high-efficiency steam turbines and mills could significantly enhance the economic and environmental sustainability of the sugar industry. The feedstock, technology and market for bagasse-to-energy production are already accessible, making this an immediate and practical opportunity to create value from waste.
4. **Limitations of Advanced Technologies**
   However, adopting highly advanced technologies—such as on-site enzyme production for ethanol fermentation, wastewater treatment systems, or the production of bio-based chemical building blocks—may be impractical at this stage. These technologies require advanced skills, significant investment and a supportive business climate, all of which are currently limited in Jamaica. Implementing such solutions prematurely risks failure and inefficiency.

Excursus 33.2 EU Project: Circular Bio-Based Business Models to Create High-Value Bio-based Products in Integrated Value Chains (C4B)

Inclusive Innovation is also promoted and supported in the context of the development of new regional bio-based value chains in Europe, for instance, within the EU-funded research project C4B. While primary producers are essential stakeholder of the European circular bioeconomy, their involvement in innovative bio-based business models is still limited. In most cases, the benefits are not fairly distributed along the value chain, to the disadvantage of primary producers.

The goal of the project C4B is to build fair and sustainable business models that create opportunities for rural entrepreneurship and allow farmers to participate in value-adding activities. The project comprises nine case studies across Europe, including forestry in Sweden and Italy, vineyards in Greece and Italy, cereal production in Greece and Italy, apple production in the DACH region, potato production in southern Germany and wetlands in northern Germany. During the first phase of the project, different biomass conversion pathways of harvest residues are explored with primary producers and other stakeholders. The focus is on developing high value-added products, including biochar, platform chemicals, and products for the food and cosmetics industries. In the second phase, inclusive business models will be design and evaluated based on scalability and replicability, as well as sustainability.

Sharing of power and profits across novel bio-based value chains may accelerate the development of rural communities, the local addition of value and farmers' economic diversification, as well as enhance the cooperation among farmers, foresters and bio-based industries (► www.c4b-project.eu).

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33.4.1 Adapting for Future Capabilities

Should the bio-based value chain succeed, it could enhance the local community's capabilities by providing access to investment funds and higher education opportunities. This, in turn, could create favourable conditions for incorporating advanced technologies. For instance, a biorefinery initially focused on first-generation production can later be expanded with more complex, second-generation technologies to optimise energy use and diversify outputs. This adaptability makes biorefineries particularly well-suited for fostering new capabilities and enabling a gradual shift towards higher-tech applications.

By combining strategies that respect existing capabilities, foster new skills and invest in future potential, actors can create sustainable, inclusive value chains that adapt to local realities while laying the groundwork for growth and innovation.

33.5 Conclusion

The bioeconomy promises economic prosperity and ecological sustainability by replacing fossil resources with biomass. However, these developments raise critical questions about economic and environmental justice. Key concerns include who benefits from these technologies, ownership and distribution rights, their impact on global inequalities, especially given that much biomass will come from the Global South and be processed in the Global North, and their contributions to sustainability.

For developers of emerging bio-based value chains, this implies the need for careful consideration of local circumstances and the skills, needs and values of local producers of biomass. Focusing solely on participatory exercises is not sufficient (De Gelder and Asveld 2024). Insights from local stakeholders need to be translated to actual design choices. Key choices in the development of inclusive value chains comprise feedstock

selection, biorefinery design and often also type of contracts (Robaey et al. 2022). Relevant aspects that need to be considered include local learning practices, local farming culture, local access and ownership of technology, infrastructure, and access to markets and access to information. All these elements determine the level of inclusion that is feasible for local producers of biomass (De Gelder and Asveld 2024).

There is a risk that sustainability is understood mainly as efficient production; however, truly sustainable and reliable value chains need to accommodate the capabilities of local stakeholders. Local contexts can be complex, and many different factors play into the quest for effective inclusion. Understanding this context and integrating it into the design of value chains can be a daunting task. Commercial parties have a role to play, but considering the sometimes substantial risks in developing inclusive value chains, as well as the potentially great benefits, governmental bodies should also step in and shoulder some of the burdens.

Do you want to learn more about the concept of responsible and inclusive innovation? Take a look at Supplementary Material 33.1, a video from our MOOC "Concepts of Sustainable Bioeconomy" (2021).

Questions

1. What is the relevance of environmental justice for the bioeconomy?
2. What would inclusive innovation imply for biobased products?

Answers

1. The bioeconomy has the potential to create jobs and foster economic growth. Environmental justice ensures that these opportunities are distributed equitably, providing marginalised groups with training, resources and infrastructure to participate in and benefit from bio-based industries. Environmental justice frameworks stress the importance of including affected communities in decision-making processes regarding bioeconomy projects and policies. This ensures that their voices are heard, and their needs and concerns are addressed. The transition to a bioeconomy must not perpetuate the exploitation of land and labour in vulnerable communities. Environmental justice frameworks help identify and mitigate risks of land grabs, unsustainable practices or unequal labour conditions that disproportionately harm these groups.
2. Inclusive innovation aims to expand both the target audience of an innovation and the range of stakeholders involved in its development and design. The focus can be on the product design itself, incorporating various stakeholders' perceptions to create a more inclusive design or taking a comprehensive approach that also considers the local context of production.

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Entrepreneurial Ventures and the Bioeconomy

Andreas Kuckertz, Elisabeth S. C. Berger, C. Arturo Morales Reyes, and Sebastian Hinderer



Fig. 34.0 Entrepreneurial Ventures and the Bioeconomy. (© Universität Hohenheim, Corinna Schmid) (▶ https://doi.org/10.1007/000-hvf)

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Entrepreneurship is based on entrepreneurial opportunities, and the bioeconomy offers a plethora of such opportunities. By acting upon such opportunities, entrepreneurs make an important contribution to the bioeconomy transition. As the bioeconomy, to a large extent, addresses humanity's greatest challenges, it consequently offers the greatest entrepreneurial opportunities as well. One useful tool to break down the idea generation process and manage the entrepreneurial process is the business model canvas, which makes it possible to clearly describe the value proposition of a new venture in the bioeconomy. The lean startup approach can help entrepreneurs in the bioeconomy to move efficiently through the entrepreneurial process and to quickly develop a value proposition and a validated business model.

Learning Objectives

After studying this section, you will…

- …be able to describe the role of entrepreneurship in the bioeconomy transition (see ► Sect. 34.1).
- …be able to describe the challenges the bioeconomy faces and to interpret them as entrepreneurial opportunities (see ► Sect. 34.2).
- …be able to name the essential tools that entrepreneurs in the bioeconomy can use to manage the startup process (see ► Sect. 34.5).
- …be able to summarize the first steps necessary to become an entrepreneur in the bioeconomy (see ► Sect. 34.5).

34.1 The Role of Entrepreneurship in the Bioeconomy Transition

Humans being conscious of their footprint on this planet is not a novelty. More than 50 years ago, the Club of Rome (Meadows et al. 1972) introduced the world to different model-based scenarios that illustrated the limits of economic growth, which directly correlate with the finite natural resources of planet Earth. Despite significant public awareness, those same issues remain pressing and relevant. The bioeconomy addresses these challenges, but the transition to it will not happen overnight.

Innovation and technological progress within the bio-based sector and investments in this sector remain the main bottleneck for the bioeconomy transition (Hinderer et al. 2021). Government interventions might be one solution, but the potential of private initiative from entrepreneurs in driving the bioeconomy transition is immense (Kuckertz and Wagner 2010). Bioeconomy strategies worldwide recognize the pivotal role of entrepreneurship in this transition, but there is a need to bolster support for bioeconomy startups (Kuckertz et al. 2020). Fortunately, innovative bioeconomy entrepreneurs are not alone in their journey. They receive support from various players in the entrepreneurial ecosystem, such as investors, universities, and government agencies (Kuckertz et al. 2020). So, eventually, they might be able to scale their business solutions to a broader range of customers (Hinderer and Kuckertz 2024) and create value for a wider group of beneficiaries. Figure 34.1 visualizes the role of startups in the bioeconomy transition.

Do you want to learn more about entrepreneurship in the bioeconomy? Take a look at Supplementary Video 34.1, a video from our MOOC "Concepts of Sustainable Bioeconomy" (2021).

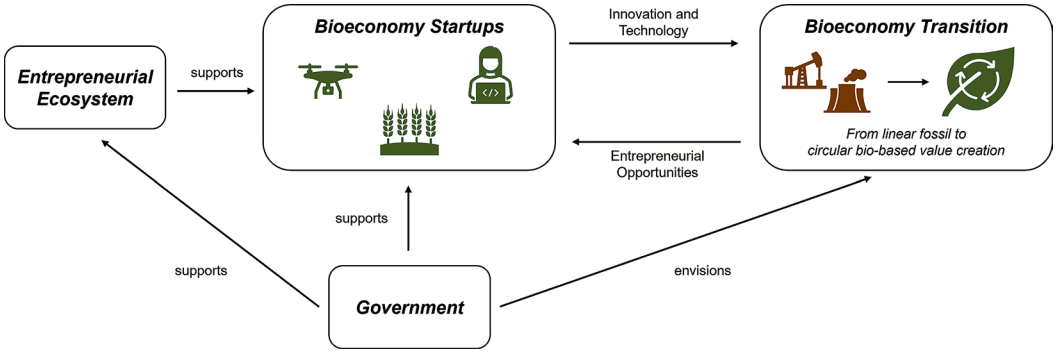


Fig. 34.1 The role of bioeconomy startups in the bioeconomy transition (based on Kuckertz et al. 2020; Hinderer and Kuckertz 2022a)

34.2 Entrepreneurial Opportunities and the Bioeconomy

Providing business solutions to accomplish the switch from our current fossil fuel-based economy is the main task of entrepreneurs in the bioeconomy. Entrepreneurs are likely to provide valid answers to questions like how we might produce more with less and how we can secure more high-quality food, more energy, and more social stability with fewer resources, less space, less water, less energy, and less risk.

Addressing those challenges with a meaning in mind and not with a given fixed set of objectives and resources is an ongoing process in which entrepreneurs use their existing networks to accomplish targets that will eventually lead to newly established companies addressing the challenges of the bioeconomy. This situation is not solely based on an altruistic mindset but rather the starting point for a business opportunity in areas such as energy, food security, and resource efficiency.

Several barriers hinder the development of the bioeconomy. Companies and individuals might be aware of the threats to planet Earth, but at the same time, business practices today often do not value, for instance, free natural assets. Therefore, natural assets are especially prone to abuse by society and individuals (Dorfman 1993). Governments might provide funds and support to reduce this market failure (see ► Sect. 28.2.1). However, at the same time, market failure, which has an environmental impact, provides grounds for many entrepreneurial opportunities in the bioeconomy.

> An ***entrepreneurial opportunity*** is the opportunity to establish a new firm, which in the bioeconomy often results from market failure. Huge market failures provide huge opportunities for entrepreneurs to establish new ventures that create value by addressing the challenges facing humanity.

If the market failure creates a problem, an individual can engage in entrepreneurial activity and generate profit by discovering the opportunity to provide a solution, evaluating the opportunity, and ultimately exploiting it by providing the solution (Shane and Venkataraman 2000; Dean and McMullen 2007). When providing such bioeconomic solutions, entrepreneurs contribute to the mitigation of market failure and hence to the development of the bioeconomy, which holds the promise to ensure the quality of life on Earth and also for future generations (Berger and Blanka 2024). The bioeconomy and the underlying principle of cascade biomass usage offer a plethora of entrepreneurial opportunities and thus enable the formation of bioeconomy startups exploiting these opportunities (Hinderer and Kuckertz 2022b). The *Visioverdis* case study is a perfect example of

the tremendous creativity that bioeconomy startups can apply to address the enormous challenges of the bioeconomy.

What exactly constitutes an entrepreneurial opportunity has been debated in the academic literature for quite some time (Kuckertz et al. 2017). There seems to be consensus that the process of recognizing entrepreneurial opportunities involves being alert, actively searching for them, and gathering information about new ideas on products or services. Economic theory (Schumpeter 1934; Kirzner 1973; Drucker 1984) suggests that entrepreneurs should particularly look for four different types of trends and developments, as these are likely to trigger entrepreneurial opportunities. These are:

- Information asymmetries and incongruences
- Exogenous shocks
- Changes in demand
- Changes in supply

For instance, it appears obviously incongruent that each year, millions of people die of hunger caused by the scarcity of water and agricultural land. In contrast, at the same time, in the developed world, 'redundant' food is being destroyed. Resolving such incongruity constitutes an opportunity for bioeconomy entrepreneurs. Similarly, climate change (or other earth system processes that are in danger (Richardson et al. 2023) could be interpreted as exogenous shocks that are likely to be addressed with new technologies brought to the market by innovative entrepreneurs. In a similar vein, such exogenous shocks can prompt changes on the demand side: end consumers now tend to want ethical, green, and sustainable products and services, and entrepreneurs can cater to such desires with new offerings.

Excursus 34.1. Case Study Visioverdis: THE GRAVIPLANT (Fig. 34.2)

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Alina Schick, a biologist with expertise in botany with a focus on plant physiology who received her PhD in agricultural sciences from the University of Hohenheim in Germany, has been wondering about one of those significant challenges for society. More specifically, Alina has been asking herself: How should the cities of the future be designed? If population density is concentrated in metropolitan areas, how can air pollution be minimized? Pollution concentration in major cities also brings two significant side effects: Green areas tend to disappear, and land prices increase exponentially, making it almost impossible to have parks in the city or maintain existing green areas.

Alina's startup, Visioverdis (2017), solves this problem with the GraviPlant, a tree that can be installed on building facades and grows perpendicular to the wall. The idea is based on Alina's doctoral studies, during which she managed to grow trees horizontally by rotating them on their axis and giving them precise doses of water and nutrients (Clinostat). After testing different types of trees and building the prototype, she proved the existence of a business opportunity for her research by participating in and winning several startup idea competitions. In 2017, Visioverdis managed to acquire a contract to integrate trees into the facade of the building designed for the world show that celebrates the 500th anniversary of the protestant reformation in Wittenberg, which offers an opportunity to present the idea to a global audience.

The tree rests in a sealed container with a high-tech plant care system. The container is just docked to a water pipe, and the tree grows fully independently, requiring no maintenance for four years. Currently available solutions (like vertical planting systems or creeper plants), in contrast, require constant maintenance to prevent damage to the building's infrastructure. Visioverdis' goal is not only to conquer the European market but also to unleash the potential of the GraviPlant in countries that currently suffer from severe air pollution and drought, such as China and Saudi Arabia.



Fig. 34.2 The GraviPlant. © Universität Hohenheim, Corinna Schmid

Given the substantial failure rates of entrepreneurial ventures, entrepreneurs need to assess whether a particular opportunity has the potential to be turned into a profitable business. There is obviously no way to do so in an objective and completely reliable manner. However, to assess whether an entrepreneurial opportunity is attractive, it may help to think about these opportunities as a professional investor would. That investor might be a venture capital firm (Kollmann and Kuckertz 2010) or a unit investing in promising startups on behalf of a larger corporation (Roehm et al. 2018). Such investors would look for opportunities:

- Where entrepreneurs can create significant value for customers or users
- Where the opportunity matches the experience and competence of the entrepreneur or the venture team
- Where a significant problem is addressed, or needs will be met for which customers are willing to pay a significant premium
- Where they can be active in a large and growing market
- Where there is a balance of risk and potential

The potential to become entrepreneurially active in the bioeconomy is therefore enormous, as an equilibrium of natural sources and an ideal bioeconomy is unfortunately not yet in sight. This situation is fertile ground for entrepreneurial activity.

> "***Bioeconomy startups*** are the result of new venture creation that is externally enabled by the bioeconomy transformation. They seize the opportunities for entrepreneurial activity provided by the bioeconomy transformation by producing biological resources, offering products and services related to the production of such resources, and/or by using biological resources and processes to offer products or services related to food, feed, bio-based products, and energy, all the while considering sustainability and circularity." (Hinderer and Kuckertz 2022b, p. 2951)

34.3 Managing the Startup Process in the Bioeconomy

In general, entrepreneurship deals with the question of how individuals effectively organize any growth-oriented creation process on the basis of opportunity (Kuckertz and Mandl

2016). Having an idea of what product or service in the bioeconomy customers could benefit from is thus often the first step toward exploiting such an entrepreneurial opportunity and founding a startup (Kuckertz et al. 2017). However, traditional market research instruments often fail to assess the potential of a product or service that does not yet even exist. The only way to find out is to develop and test the product early.

A popular approach to becoming entrepreneurially active is the lean startup method, which describes founding a business in a very lean and resource-conscious manner. It stands in opposition to more traditional approaches to managing the startup process that usually include writing a detailed business plan and approaching the market only when a close-to-perfect offering has been developed. The lean startup method is related to the Japanese car manufacturer Toyota's lean manufacturing, an approach seeking to eliminate as much waste as possible from production processes (Womack and Jones 1996). Similarly, the lean startup method seeks to eliminate as much unnecessary effort as possible from startup processes.

A ***business model*** explains the key components of a business and how they relate to each other in order to create value.

Eric Ries (2011) is credited with applying lean principles to founding startups. The lean startup method is an iterative and agile method to develop a startup based on listening to the needs of potential customers and testing their willingness to pay for the service or product offered by the startup. During the process, the focal question is whether the product or service solves a real problem for real customers and whether a valid business model can be developed. Instead of planning for the future, the aim is to learn by doing and by introducing the product or service to the market as early as possible. This approach naturally involves a risk of failure, but as failure can never be avoided entirely, it is reasonable to embrace it as early as possible. Failure creates opportunities to learn and try again to succeed (Blank 2013a). Thus, many entrepreneurs go through many failed projects before they eventually find a valid business model (Mandl et al. 2016).

The first step of the lean startup method involves making basic assumptions concerning possible customer requirements and the potential market. Assumptions should initially be validated by talking to and listening to potential customers. The potential failure and learning then need to be enabled quickly by developing a so-called *minimum viable product.* For instance, the German startup *nevi* nowadays produces and sells luxury surfaces for furniture, bathrooms, and spas, as well as yachts made from birch bark, which is a waste product from the paper industry (nevi GmbH 2023). To do so, *nevi* started testing the market potential of birch bark with different minimum viable products in different industry segments, such as handlebar grips for bicycles.

The ***minimum viable product*** constitutes a reduced offer that is subjected to customer feedback as quickly and often as possible in order to test a startup's hypotheses about actual market needs.

The minimum viable product represents a prototype that might be far from perfect, but which works. Once there is a minimum viable product, the *build-measure-learn* cycle can be initiated (Blank 2013b). The cycle aims to enable validated learning by continuously improving the minimum viable product based on customer feedback. The development of the minimum viable product toward a functioning business model might include numerous incremental changes. However, it might also require a *pivot,* that is, a more radical correction from the original idea toward new value creation if some underlying assumptions prove invalid.

Especially in the bioeconomy with potentially highly innovative products, customers

and entrepreneurs might need to discover the product's added value together to arrive at a functioning business model. The minimum viable product illustrated in Fig. 34.3 exemplifies the incremental change in farming tools according to the needs of the farming sector. Even the first approach to a farming tool is fully functional, but it takes several iterations to arrive at the final, smart solution. While a minimum viable product helps to test the market, it is not sufficient to build a company around it. Instead, entrepreneurs need to think in terms of business models, which answer the question of what key components of the company interact to generate value for the customer and, therefore, provide a competitive advantage for the company.

The business model canvas is a powerful, iterative tool (Fig. 34.4) to think beyond a specific idea or product and develop the business model. The canvas consists of nine distinct components that describe how an organization creates, delivers, and captures value (Osterwalder and Pigneur 2010). The business model canvas is helpful for understanding and visualizing the interplay of the different components that create value. While it might be valuable to understand existing business models, the business model canvas is also suitable for designing business model innovations, which describe novel approaches toward the design of single components and the interplay of such components.

The canvas can be compared to a theater. The left side of the canvas represents the backstage, the creative arena of the organization, which is usually not visible to customers. The right side of the canvas represents the stage, the value part of the organization, which needs to be transparent to customers. The nine components of a business model are described below based on the bioeconomy startup Holiroots (Excursus 34.2).

> The ***business model canvas*** combines nine components associated with a firm to illustrate how value is created and can be utilized to understand existing business models but also to create innovative business models.

Central to the business model is the value proposition, which addresses the added value the company provides to its customers. The value proposition of Holiroots is to offer a

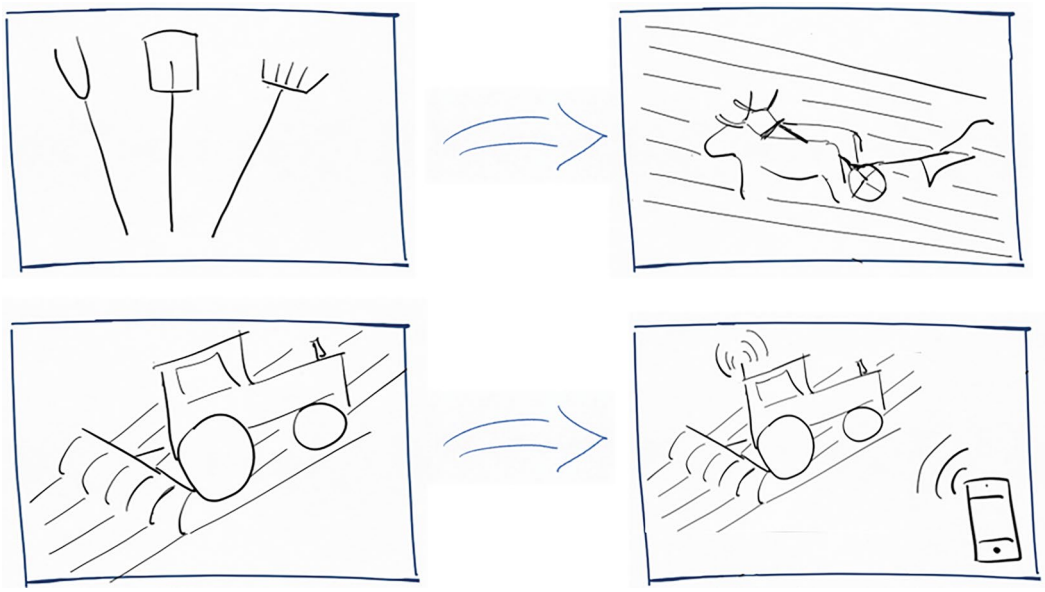


Fig. 34.3 Minimum viable product of basic farming tools developing into software-based precision agriculture. (© C. Arturo Morales Reyes)

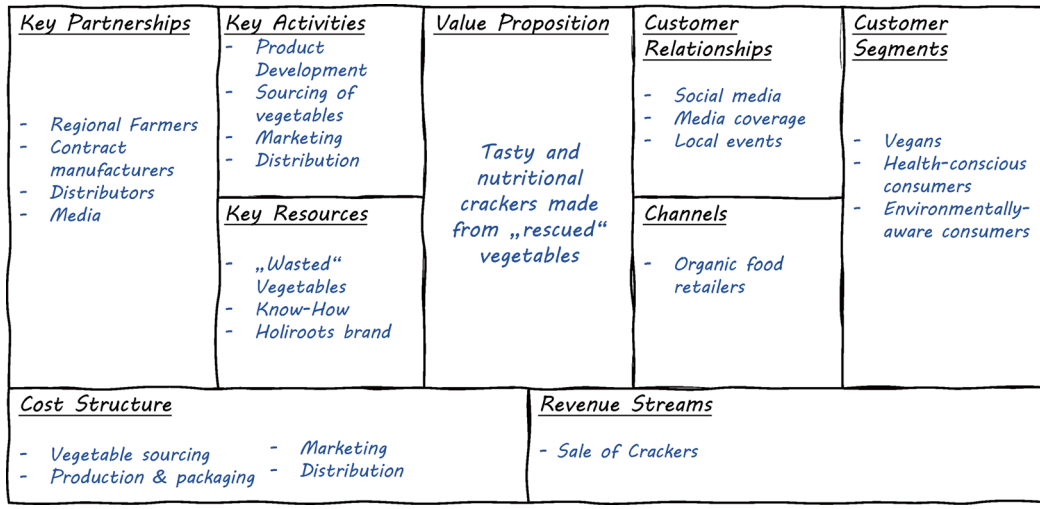


Fig. 34.4 Holiroots Business Model: Depicted using the business model canvas provided by Osterwalder and Pigneur (2010) for the case of Holiroots (2024). (© Sebastian Hinderer)

tasty and healthy snack alternative by transforming vegetables that would otherwise go to waste into nutritious crackers. These products are organic, vegan, high in fiber, and have a lower calorie count than many conventional snacks. The value proposition might be different for each customer segment, and the term describes for whom the company creates value. Holiroots targets health-conscious consumers, environmentally aware individuals, and the vegan product market.

Of course, these customer segments may overlap at times. The channels are used to reach customers and point out the value proposition to them. Holiroots uses partnerships with organic food retailers. The customer relationships describe how the relationships with the relevant customer segments are created and maintained. Holiroots fosters a strong community connection by engaging with customers through social media, providing educational content about food waste, ensuring media coverage regularly, and participating in local sustainability events to promote their products. Revenue streams are generated through selling the value proposition. In other words, it answers the question of where the money is made. Holiroots generates revenue from the sale of its vegetable crackers through retail partners. They may also explore additional revenue streams, such as collaborations with restaurants and cafes.

Excursus 34.2. Case Study Holiroots: Transforming Food Waste into Nutritious Snacks (Fig. 34.5)

Holiroots was founded by Paola Varela and Duyen Do during their master's degree in Bioeconomy at the University of Hohenheim, Germany. This innovative startup addresses a critical issue in the agricultural and food industry: food waste. By producing and selling crackers made from vegetables that farmers cannot sell to food retailers due to deficiencies in size or shape or due to overproduction, Holiroots not only provides a sustainable solution to food waste but also generates additional income sources for regional farmers (Holiroots 2024).

Every year, a significant amount of vegetables is discarded because they do not meet market standards, contributing to a substantial loss of resources and income for farmers. Holiroots partners with these farmers to rescue surplus and imperfect vegetables, preventing them from going to waste. The rescued vegetables are processed into high-fiber, low-calorie vegetable

crackers, which are organic and vegan, catering to the growing market of health-conscious and environmentally aware consumers. These products offer a nutritious alternative to conventional snacks, aligning with the company's commitment to sustainability and health.

In addition to producing healthy snacks, Holiroots actively engages with the community through educational campaigns and participation in local sustainability events. By raising awareness about the issue of food waste, they aim to inspire broader societal change and encourage more sustainable consumer behaviors. Holiroots shows how a startup can successfully combine innovation with social and environmental impact. Through their efforts, they are making a significant contribution to reducing food waste, supporting local farmers, and providing consumers with a healthy, eco-friendly snack alternative.



Fig. 34.5 Holiroots co-founder Paola Varela. © Holiroots

The components on the left side of the model determine whether the revenue streams are sufficient to make the business model work. The key activities are required to create the value proposition. In the case of Holiroots, these activities include sourcing imperfect and surplus vegetables, producing crackers, marketing, and distribution. The key resources are needed to realize the key activities. For Holiroots, these resources include the vegetables, the know-how to produce the crackers, and the brand itself. The activities and resources might be internal or come from a key partner outside the organization. Holiroots cooperates with several key partners, such as regional farmers who supply

imperfect or surplus vegetables, contract manufacturers, and retail partners who distribute the products. Another key partner for Holiroots is the media, which helps raise awareness about their mission and products. Investors and stakeholders supporting sustainable business practices can also be key partners. The left side of the business model canvas creates costs, which form the cost structure of the business model. In other words, the left side of the plan answers the question of how much it costs to create value. Holiroots' cost structure includes vegetable sourcing, production, packaging, marketing, and distribution expenses.

The goal of any entrepreneur is thus to create a business model that creates value and a favorable balance of cost structure and revenue streams. A firm can only say it has a viable business model when this goal has been achieved. Holiroots demonstrates this balance by efficiently transforming waste into value, thus contributing to a more sustainable food system.

Hands-on: Let's get started! If you have an idea, that is great! We just managed to motivate you to change the world. Here, you will find a simplified set of steps that can help you to get started. First, check your idea. To create a better world is always a great starting point for any startup. However, at some point, you will need money to advance your idea. Therefore, the basis for a financially sustainable company is an idea with market potential.

Use the following "W" questions to test the market viability of your idea. If you cannot answer all the questions, that is ok. Answering them all is a learning process you will have to go through. Remember? Build, measure, learn!

1. What is the business idea?
2. What makes your idea unique?
3. Who are the customers, and how big is the target group?
4. What is the business model?
5. Who are the competitors? (includes products/solutions similar to yours)
6. Who is part of the founder team? Who is missing?

Once you can answer all these questions, you should take four steps that can help to develop your idea further and move toward a sustainable business model in the bioeconomy:

1. Join a startup event in your city and get to know the startup scene in town. These events are the perfect place to network and exchange your ideas with others.
2. Pitch your idea and discuss it with people you do not know. In this way, you can obtain valuable input about the first problems your idea may encounter.
3. Find a team that can help you to make your idea a reality. Only when the entire team shares the same vision can objectives be accomplished.
4. Work with the business model canvas intensively. Moreover, look for a mentor who can provide valuable feedback.

Questions

1. Why is entrepreneurship important for the bioeconomy transition?
2. Define the term *minimum viable product*.
3. What are the first steps in developing a sustainable business model in the bioeconomy?

Answers

1. Entrepreneurship is crucial for the bioeconomy because it drives innovation and the development of sustainable, bio-based solutions that address environmental challenges. Entrepreneurs are agile and adaptable, enabling them to quickly respond to new market opportunities and attract investment to scale their technologies. Through job creation and market transformation, they play a pivotal role in shifting industries toward greener, more sustainable practices.
2. The Minimum viable product constitutes a reduced offer that is subjected to customer feedback as quickly and often as possible in order to test a startup's hypotheses about actual market needs.

3. If you're looking to turn your idea into reality, a great first step is to join a startup event in your city. These events are ideal for getting to know the local startup scene, networking, and exchanging ideas with like-minded individuals. Once you're there, pitch your idea and engage in discussions with people you don't know; this will give you valuable insights into the potential challenges your idea may face. Next, focus on building a team that shares your vision and can help you bring your idea to life—success is more achievable when everyone is aligned toward the same goals. Finally, work intensively with a business model canvas to solidify your plan, and seek out a mentor who can offer constructive feedback, helping you refine your approach and avoid common pitfalls.

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Sustainability Management at Corporate Level

Iris Lewandowski and Moritz Wagner



Fig. 35.0 Sustainability management at corporate level. (© Universität Hohenheim, Wolfram Scheible) (► https://doi.org/10.1007/000-hvg)

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There are several motivations for a company to pursue sustainability. Among these, the fulfilment of legal requirements is the strongest driver, but societal pressure and sustainability as a marketing tool can also be important incentives. This chapter focuses on aspects that are relevant for companies building sustainable bio-based value chains. The role of life-cycle assessment (LCA) is described, particularly in relation to GHG accounting. Sustainability standards and certification systems, such as the Roundtable on Sustainable Biomaterials (RSB), and supply chain traceability models are also presented. Finally, the new EU due diligence obligations are discussed.

Learning Objectives

After studying this section, you will…

- …be able to describe sustainability tools relevant to companies developing bio-based businesses (see ► Sects. 35.1, 35.2, 35.3, and 35.4).
- …be able to explain how life-cycle assessment (LCA) can support sustainability management in the bio-based industry (see ► Sect. 35.1).
- …be able to comment on certification systems, supply chain models and due diligence obligations relevant to building sustainable bio-based supply chains (see ► Sects. 35.3 and 35.4).

There are various motivations for a company to engage with sustainability. The fulfilment of legal requirements is clearly the strongest driver. As key economic players, companies are under increasing pressure from a range of different stakeholders to engage in sustainability management and make their contribution to sustainability. A number of tools are available to companies in the area of sustainability and management control, as well as sustainable supply chain management. These are described in the textbook "Sustainability Management" (see Hahn 2022) and are not further elaborated here. The following sections focus on sustainability aspects with particular relevance for bio-based value chains and industries.

Major sustainability challenges for bio-based industries include societal demand for sustainable biomass supply chains and delivering on the sustainability promises of the bioeconomy, particularly with respect to climate change mitigation. This has been highlighted by the lessons learned during the development of the biofuels sector over the past decades (Lewandowski 2015).

Sustainability reporting obligations were introduced for the biofuels industry in Europe in 2009 with the Renewable Energy Directive (RED), which provides the legal framework for the development of clean energy in all sectors of the EU economy. This was accompanied by the obligation for suppliers to blend a specific proportion of sustainably certified biofuels into the fuels they produce. According to Directive (EU) (2018/2001), the most important sustainability requirement for biofuels is a minimum reduction in greenhouse gas emissions through the use of biofuels, bioliquids, and biomass fuels. This must be at least 65% for biofuels, biogas consumed in the transport sector, and bioliquids produced in installations that come into operation on or after 1 January 2021.

However, GHG emissions and savings are just one of the many sustainability criteria for bio-based value chains. This is reflected in the development of the Roundtable on Sustainable Biomaterials (► RSB) sustainability standard for biofuels and biomaterials, which, similar to other certification systems for agricultural and forestry products, contains traceability requirements to ensure the identity of labelled material.

The following subsections describe how LCA tools (see ► Sect. 41.2.1) can support companies in assessing their sustainability and GHG performance. Suitable certification systems that can be applied in bio-based value chains are presented, as are traceability and due diligence approaches. Finally, the role of supply chain collaboration for the development of sustainable bio-based value chains is addressed.

35.1 Life-Cycle Assessment (LCA)

As illustrated in ▶ Sect. 31.1 and in a more detailed account of the LCA method in ▶ Sect. 41.2.1, life-cycle assessment is an internationally recognized method for the holistic analysis of potential environmental impacts of products and services over their entire lifetime, standardized in two ISO norms (14040/14044). Currently, the primary application of the LCA approach in sustainability management at the corporate level lies in the fields of accounting and reporting of greenhouse gas (GHG) emissions. These practices are essential not only for regulatory compliance but also for demonstrating corporate responsibility, improving operational efficiency, and enhancing stakeholder trust. To achieve this, companies must first assess their GHG emissions. This involves the systematic process of quantifying and managing greenhouse gas emissions from corporate activities. Companies must identify all potential sources of GHG emissions within their operations, including direct emissions from owned or controlled sources (Scope 1), indirect emissions from the generation of purchased electricity (Scope 2), and other indirect emissions from the value chain (Scope 3). Here, accurate data collection is paramount.

So far, companies employ various tools and methodologies, such as the ▶ Greenhouse Gas Protocol, to report GHG emissions. These involve the collection of data on energy consumption, waste generation, transportation, and other relevant activities. Using standardized emission factors, companies convert the collected data into GHG emissions. This ensures that emissions are quantified in terms of carbon dioxide equivalents (CO_2eq), enabling a consistent and comparable metric. Once GHG emissions have been accurately accounted for, transparent reporting, whereby companies must provide a comprehensive disclosure of their GHG emissions, is required. This typically includes a breakdown of emissions by scope, a discussion of the methodologies used, as well as an explanation of any significant changes or trends in emissions over time. To enhance credibility, many organizations seek third-party verification of their GHG data. This independent verification ensures that the reported data is accurate and reliable, bolstering stakeholder confidence. GHG emissions data should be integrated into broader sustainability reports, such as those aligned with the Global Reporting Initiative (▶ GRI) standards or the Sustainability Accounting Standards Board (▶ SASB) frameworks, as such integration helps stakeholders to understand the full context of a company's environmental performance.

Implementing robust GHG accounting and reporting practices offers several benefits:

- *Regulatory compliance*: As governments around the world tighten regulations on GHG emissions, having accurate and comprehensive GHG data ensures that companies can comply with legal requirements and avoid potential penalties.
- *Risk management:* Understanding and managing GHG emissions helps companies identify potential risks related to climate change, such as regulatory changes, physical impacts, and market shifts. This proactive approach enables better strategic planning and risk mitigation.
- *Operational efficiency:* Tracking GHG emissions often highlights inefficiencies in energy use and other processes. Companies can then implement targeted measures to reduce emissions, which can also lead to cost savings and improved operational efficiency.
- *Enhanced reputation*: Transparent GHG reporting demonstrates a company's commitment to sustainability and environmental responsibility. This can enhance brand reputation, attract environmentally conscious consumers, and strengthen relationships with investors and other stakeholders.
- *Market advantage*: As more consumers and investors prioritize sustainability, companies that excel in GHG management and reporting can differentiate themselves in the marketplace. This can lead to increased market share and investment opportunities.

In the context of corporate sustainability management, GHG accounting and reporting are indispensable tools for understanding, managing, and communicating environmental impacts. By investing in robust GHG accounting practices and transparent reporting, companies can not only comply with regulations but also increase operational efficiencies, mitigate risks, and build a strong reputation for sustainability. As the global focus on climate change intensifies, these practices will become even more critical for long-term business success and resilience.

35.2 Certification

In 2007, the Roundtable for Sustainable Biofuels (RSB) was established as an academic initiative to respond to the sustainability risks posed by the growing focus on biofuels. In 2013, the RSB was formally registered as a not-for-profit association, advancing its mission to a sustainable transition to a bio-based and circular economy. Its name has since been changed to the Roundtable on Sustainable Biomaterials (RSB). The RSB currently has over 130 members from industry, environmental and civil society organizations, academic institutions, and UN and government bodies. It provides a sustainability standard with "12 Principles & Criteria (P&C) […] describing the best of social, legal, environmental and management practice for sustainable production in the biocircular economy" (More information can be found ▶ here and in ◘ Fig. 35.1).

The RSB provides the most comprehensive sustainability certification system for the circular bioeconomy, as it also includes principles on local food security and GHG emissions. These principles distinguish it from most certification systems for the agricultural sector (see ▶ Sect. 31.2), which tend to focus on good agricultural practice or a single aspect such as animal welfare (see ◘ Table 31.1).

Certification systems provide assurance (through a certification mechanism) that certain characteristics or attributes of the product or its production method or production system have been met (Chever et al. 2022). They provide standards ideally agreed through a multi-stakeholder approach that can be considered sustainability standards. Certification can, therefore, help a company to assure customers of the sustainability performance of



◘ **Fig. 35.1** Principles & Criteria (P&C) of the RSB sustainability standard

its products, either to meet increasing customer pressure for such sustainability assurance or to use the sustainability label for marketing purposes.

In general, certification systems are also considered helpful tools for the development of sustainable supply chains and the fulfilment of due diligence obligations. For this purpose, Spiller et al. (2023) recommend the Fairtrade certification scheme and the Food Security standard. ► Fairtrade™ focuses on social aspects, particularly the empowerment and fair remuneration of smallholder farmers and workers, and the strengthening of local communities. The Food Security Standard (► FSS) is also designed to help companies fulfil their social responsibilities. Through its systemic approach, the FSS enables the requirements of human rights obligations in agricultural production to be taken into consideration. With its measurable and practical criteria, the FSS provides companies with a toolbox for complying with and fulfilling their human rights due diligence obligations.

35.3 Due Diligence

In the EU, due diligence obligations arise in particular from the "EU Regulation on Deforestation-Free Supply Chains (EUDR)," which came into force in summer 2023, and in Germany from the "German Act on Corporate Due Diligence Obligations in Supply Chains (*Lieferkettensorgfaltspflichtengesetz*, LkSG)," which took effect in early 2023. The EU is also developing a proposal for a "Directive on Corporate Sustainability Due Diligence (CSDDD)." In this context, due diligence is an assessment process in which strengths, weaknesses, opportunities, and risks are analyzed, particularly with regard to social, but also economic and ecological factors.

Spiller et al. (2023), who analyzed the impacts of the LkSG on companies in the agri-food sector, see the supply chain due diligence regulations as a paradigm shift for companies. Previously, the responsibility of companies to support the achievement of sustainability goals related mainly to their own business operations. Now, companies are also held responsible for the actions of their suppliers, and moreover, even for the actions of indirect suppliers upstream in the value chain.

Collaboration within integrated supply chains is an important lever for building sustainable supply chains and fulfilling due diligence obligations. When companies have to take responsibility for their suppliers, respectful cooperation with them forms the basis.

35.4 Traceability & Supply Chain Models

Traceability and transparency are essential for building sustainable supply chains. Descriptions of supply chains are therefore required that allow companies with due diligence obligations, or consumers making choices, to obtain information on the origin of the bio-based resource. There are several approaches to enabling the traceability of the bio-based origin, known as supply chain models. In general, there are four different supply chain models, the description of which is taken from RSPO for palm oil certification:

- *Identity preserved*: RSPO Certified Sustainable Palm Oil from a single identifiable certified source that is kept separate from ordinary palm oil throughout the supply chain.
- *Segregated*: RSPO Certified Sustainable Palm Oil from different certified sources that is kept separate from ordinary palm oil throughout the supply chain.
- *Mass Balance*: RSPO Certified Sustainable Palm Oil from certified sources that is mixed with ordinary palm oil throughout the supply chain.
- *RSPO Credits/Book & Claim*: Manufacturers and retailers can buy RSPO Credits and RSPO Independent Smallholder Credits from RSPO certified growers, crushers, and independent smallholders.

In the *Identity preserved* and *Segregated* models, the consumer physically receives the certified batch of palm oil. This is not the case

with the other two supply chain models, which only ensure that a certain quantity or proportion of certified palm oil is on the market.

The *Identity preserved* and *Segregated* models are associated with the highest logistical requirements and costs. Here, the producer and supplier must provide a dedicated infrastructure for the separate transport and storage of the certified palm oil.

Book & Claim or trading with credits is certainly the model with the lowest cost and labour requirements. However, it is also criticized as being susceptible to fraud.

Questions

1. Name and describe the 4 sustainability tools that are relevant for a bioeconomy company.
2. How can LCAs help companies assess their environmental performance?
3. What are possible benefits of implementing GHG accounting and reporting?
4. Why is the use of CO_2 equivalents important when assessing emissions?
5. How do certificates help to ensure socially and ecologically sustainable production?

Answers

1. Sustainability tools that are relevant for a bioeconomy company are, for instance:
   (a) Life-cycle assessment (LCA)
   (b) GHG accounting and reporting, e.g., using the tool "Greenhouse Gas Protocol"
   (c) Supply chain models for traceability of product origin
   (d) Certification
2. With the help of LCAs, companies can identify the environmental hotspots of their operations and production processes and use the results to make decisions for improvement. LCA results can also make the environmental performance of a company or a product transparent and reportable to, for example, the customer in the biomass supply chain or the consumer of the end product.
3. These practices are not only essential for regulatory compliance but also for demonstrating corporate responsibility, improving operational efficiency, and enhancing stakeholder trust. More specifically, the benefits include:
   (a) Regulatory compliance: GHG data ensures that companies can comply with legal requirements and avoid potential penalties.
   (b) Risk management: This helps companies identify and manage potential risks related to climate change, such as regulatory changes, physical impacts, and market shifts.
   (c) Operational efficiency: Companies can implement targeted measures to reduce emissions, which can also lead to cost savings and improved operational efficiency.
   (d) Enhanced reputation: An improved brand reputation is achieved by attracting environmentally conscious consumers and strengthening relationships with investors and other stakeholders.
   (e) Market advantage: Companies that excel in GHG management and reporting can differentiate themselves in the marketplace.
4. In addition to CO2, there are other GHGs that need to be taken into account when assessing the potential climate change impacts of an operation or product. These are mainly methane (CH4) and nitrous oxide (N2O), which are 30 and 265 times more potent GHGs than CO2, respectively. CO2 equivalents are thus the weighted GHG impact of all GHG emissions.
5. Social and ecological criteria are included in certification standards. This first requires agreement on socially and ecologically relevant sustainability criteria, ideally through a multi-stakeholder approach. During the certification process, compliance with social and ecological sustainability criteria is assessed, and any shortcomings or deficiencies can be identified and potentially managed or remedied.

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Consumers in the Bioeconomy

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Fig. 36.0 Consumers in the bioeconomy (▶ https://doi.org/10.1007/000-hvh)

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This chapter sheds light on the end of the value chain: the consumer and the distinct role of retail as the place where consumers make their purchasing decisions with a focus on food. For the establishment of a bioeconomy society, it is important not only to consider the supply side but also to focus on the demand side. Thus, understanding consumer behaviour is essential for the success of the bioeconomy. This chapter is subdivided into three subchapters: It begins with an introduction to the influencing factors of consumer behaviour and appropriate research approaches to analyse these factors, delves deeper in the second part into managing consumer behaviour in the bioeconomy, and in the final part, highlights the key role that food retail plays in consumers' decision-making at the point of sale.

Learning Objectives

After studying this chapter, you will…

- …be able to describe the relevance of consumer behaviour for the bioeconomy (see ► Sect. 36.1.1).
- …be able to explain different factors that influence consumer behaviour (see ► Sect. 36.1.2).
- …be able to name and compare different methods to study consumer behaviour (see ► Sect. 36.1.3).
- …be able to name and explain two approaches to encourage sustainable consumer behaviour (see ► Sect. 36.2).
- …be able to define the food retail sector by naming its main players, i.e. the different types of companies in the sector, and critically evaluating the role of food retailing in the food value chain (see ► Sect. 36.3).

36.1 Introduction into Consumer Behaviour and Respective Research Approaches

36.1.1 Relevance of Consumer Behaviour

Consumer demand for sustainable products is on the rise. However, often, more sustainable products are more expensive in production. However, these surpluses need to be compensated along the supply chain. Further, the transition to a bioeconomy can only be successful if consumers accept and support it (Otto et al. 2021). First of all, consumers make their purchase decisions and by that exert their influence on the market. Especially when more sustainable products cost a price premium compared to conventional products, their market success depends on people's willingness to spend a surplus. It is thus crucial to understand how people perceive sustainable products from the bioeconomy, their functionality, and their environmental benefits in order to adapt products and marketing strategies. Beyond the purchase behaviour, consumers also contribute with their usage and disposal behaviour to the success of the bioeconomy. In environmental impact assessment of products (e.g. life cycle assessment, LCA), the usage phase and end-of-life treatment can account for up to 50–80% of the ecological impact of some products (Polizzi di Sorrentino et al. 2016). This should serve as a reminder not to disregard consumer behaviour, such as the use and disposal of products when it comes to environmental impact of bioeconomic products. If, for example, consumers misunderstand that 'biodegradable' means something different than 'home-compostable'

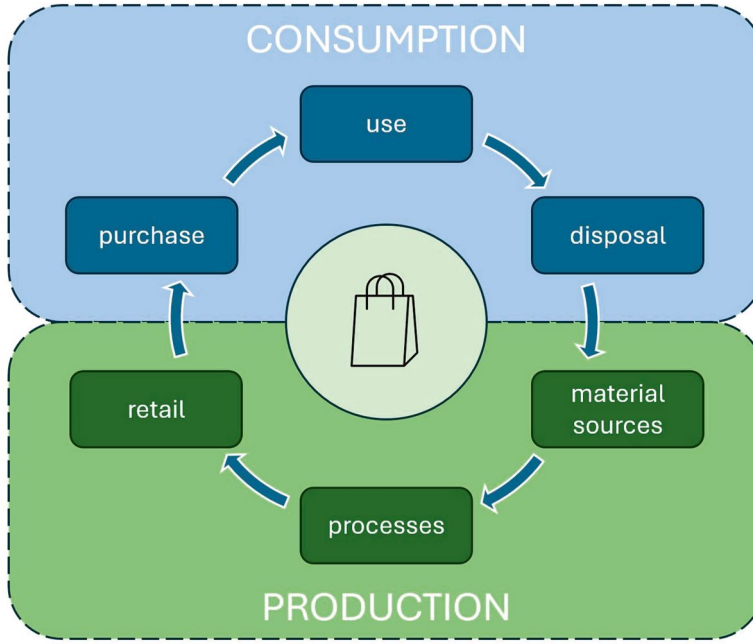


Fig. 36.1 Consumer behaviours (blue boxes) in the bioeconomy as a part of the circular interaction between consumption and production side (green boxes)

they might put bioplastics on their garden compost or litter it in nature, wrongly believing it will decompose that way. Consumers can also influence the production side by demanding more bioeconomic solutions, for example, new products or technologies that are more in line with consumer preferences for sustainable consumption. As such, consumer demand can create a market pull, encouraging companies to innovate and develop new products and markets. In Fig. 36.1, consumer behaviour is displayed in its interaction with the production side of the bioeconomy.

36.1.2 Influencing Factors

Understanding consumer behaviour is an essential part of the success of the bioeconomy. Consumer preferences can influence the development of bioeconomic products and services as explained above. Reasons for the relevance of analysing consumer behaviour are:

1. Anticipating market trends: By analysing consumer behaviour, trends and developments in the market can be identified. This enables companies to react to changes in demand at an early stage and adapt their products and marketing strategies accordingly.
2. Product development: Understanding the needs, preferences and attitudes of consumers enables companies in the bioeconomy to develop products and services that are better tailored to demand. Doing this at an early stage of product development can increase acceptance and success of novel products.
3. Marketing and communication: Communication is a very important part of marketing. Appropriate communication enables companies to develop effective marketing strategies to highlight the benefits of sustainable products and adapt it to the potential target groups. Market research is essential to identify size and characteristics of the relevant target groups.
4. Supporting policy decision makers: Policy makers in both, the private and the public sector, need information on consumer behaviour in order to develop appropriate measures and funding programs for the bioeconomy. A deeper understanding of consumer demand can help to support the

development and implementation of policy strategies.

Following Kotler et al. (2019), influencing factors on consumer behaviour can be subdivided into the following four basic categories:

Cultural Factors

First, cultural values, beliefs, norms and customs significantly influence consumer behaviour. Different cultures have different preferences, taboos and rituals that affect how individuals perceive products and make purchasing decisions. Second, there are subcultures within the cultures. These are shaped by ethnicity, religion, geographic location, hobbies or music. Subcultures may have their own unique consumer habits and preferences. The third cultural factor is the social class. Among these, socio-economic status, education level, occupation and income influence consumer behaviour in the different classes. People from different social classes may have different preferences, tastes and buying habits.

Social Factors

Peer groups can have an influence. These are groups that individuals compare themselves to seek approval from or look up to. Reference groups can include family, friends, colleagues, celebrities or opinion leaders. Their opinions and behaviours can significantly influence purchasing decisions. Another social factor is the family. Family structure, roles and dynamics play an important role in shaping consumer behaviour. Different family members, such as partners, parents or children, can have different effects and involvement in purchasing decisions. Further, roles and status are social factors of significance. A consumer's role and social status in society influence consumption decisions. For example, job title or position in society can dictate consumers' behaviours.

Personal Factors

Age and life cycle stage are also factors of influence. Consumer preferences evolve over the course of their life cycle. Age-specific needs, preferences and priorities influence purchasing decisions. Life events such as birth of offspring influence consumers' needs and also habits. Further, a person's profession and professional responsibilities can influence their purchasing behaviour. For example, professional chefs may invest in high-quality kitchens, while hobby chefs may prioritize durability and affordability. Third, consumers' lifestyles, interests, activities and opinions influence their consumption decisions. Personality traits such as extraversion, openness, conscientiousness, agreeableness and neuroticism are also influencing factors.

Psychological Factors

First, perception is a psychological factor. How consumers perceive products and brands influences their purchasing decisions. Perception is influenced by factors such as sensory stimuli, previous experiences and personal prejudices. Second, motivation is a driver for consumers' habits and consumption decisions. Consumer needs and desires drive purchasing behaviour. Maslow's pyramid of needs suggests that individuals first satisfy basic needs such as food, shelter, security needs and a feeling of social affiliation before pursuing higher needs such as self-esteem or self-actualization. Learning is another psychological factor. In that sense, consumer behaviour is influenced by previous experience, exposure to marketing stimuli and information processing. Learning through reinforcement, observation or experience shapes consumer preferences as well as e.g. brand loyalty. Consumers' attitudes and beliefs about product characteristics such as taste, safety or health claims on food packaging have an influence on their decision-making. Marketers often try to shape positive attitudes and perceptions through advertising, branding and other promotional activities. However, in research, it is often of interest to analyse food consumption behaviour at both the micro and macro levels within different environments. Thus, another way to subdivide the factors influencing especially consumers' food choice is presented in Fig. 36.2.

Following Story et al. (2008), consumers' food choices are influenced by an ecological framework which surrounds every individual. These environmental factors are:

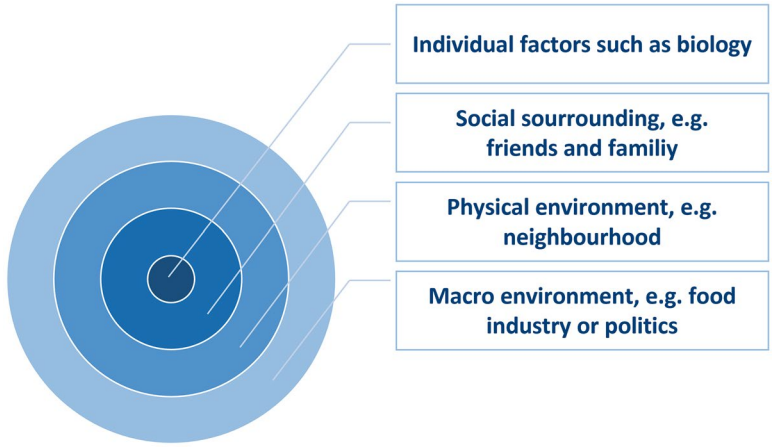


Fig. 36.2 Food environment: Factor's influencing consumers' food choice. (Based on Story et al. 2008)

1. Individual factors: biological factors such as gender or age, demographics such as income or education, attitudes, beliefs
2. Social surroundings: family, friends, peers
3. Physical environment: Supermarkets, canteens, neighbourhood, workplace
4. Macro-level environment: norms and values, food and agriculture policies, economic systems, governmental structures, food production and distribution systems

To understand how those previously explained influencing factors can be analyzed for theory or hypotheses testing, the next subchapters will briefly introduce data collection in empirical consumer research.

36.1.3 Data Collection

In order to collect data on consumer behaviour such as influencing factors, there are two general approaches: either qualitative data or quantitative data. Qualitative data is more suitable for research questions when there are no deeper insights in the area of interest yet. Quantitative data is appropriate for answering research questions and testing hypotheses, usually in cases when there is already substantial existing research in this area. The following box shows the most important differences between both kinds of consumer research approaches. Sometimes, a mixed methods approach might be appropriate.

Qualitative study	Quantitative study
A *qualitative study* is a very detailed investigation of open research questions on a small number of study units using unstructured or partially structured data collection methods	A *quantitative study* is an investigation of theoretically derived research hypotheses in many study units using structured data collection methods
Type of analysis: interpretative evaluation	Type of analysis: statistical analysis
Objective: description of subject matter including theory building	Objective: mostly theory testing
Based on Döring (2023)	

Next, there are two ways to obtain the data for these types of studies: They are either generated by primary or secondary data:

Primary data is collected specifically for research purposes, allowing it to be tailored to the exact needs of researchers. Advantages of primary data collection are: The data is usually current and relevant as it is collected directly from consumers or from the already pre-defined target groups. Beyond, research-

ers have full control over the survey methods, which makes it possible to guarantee good quality of the data and ensure that the questions operationalize exactly what is needed for the specific research question. By collecting their own primary data, organizations can develop a better understanding of consumers and markets, what can lead to competitive advantages. This is of particular importance in the field of fast-moving consumer goods, such as food, where the market is highly competitive. Besides these advantages, there are of course also disadvantages of primary data. First, cost and time. Collecting primary data can be expensive and time-consuming, especially qualitative interviews or if extensive research needs to be conducted, e.g. the requirement of large data sets. However, not all researchers, organizations or companies have the financial or human resources or infrastructure to collect primary data. Further, when carrying out e.g. industry or expert surveys, it is challenging to get enough interview partners. Additionally, primary data can be affected by various factors such as sampling bias (e.g. having no representative samples or having only participants with high involvement), response bias or interviewer bias (which could be potentially avoided by having intensive interviewer training), which can affect the reliability of the data and thus reduce the meaningfulness of the (statistical) results. This can only be partly avoided by e.g. using experimental settings (see below).

Secondary data is data that has been collected by someone for a purpose other than the current project. It is data that has already been gathered, processed and possibly analysed by other researchers, organizations or institutions. Examples are government reports, statistics, industry reports or historical records. Also, secondary data has advantages and disadvantages, which are presented in the next two paragraphs. First, using secondary data is more cost-efficient than collecting primary data because it has already been collected. Especially for scientists there is the recent option to use data which has been published by other researchers in so-called repositories. Using this data is for free. However, of course there needs to be a match between research questions and these data. Further, because secondary data is already available, (market) researchers save time that they would otherwise have to spend on data collection. Beyond, secondary data often offers broad coverage of different data sources, allowing researchers to get a comprehensive overview of the research topic. What is more, in consumer research data often provides cross-sectional data. This data is often particular interesting because it can be important to analyse consumer behaviour over a longer period such as food consumption patterns. This data is longitudinal secondary data and allows consumer behaviour comparisons over time as well as identifying and analysing trends. The most important disadvantages might be that secondary data might not provide the most recent information or may not be precisely tailored to the specific research questions. Moreover, the quality of secondary data can vary and depends on the reliability of the sources. Often, it is hard to assess how reliable the data is. It is important to note that (market) researchers often do not have control over the process of data collection and the quality of the data, as it usually comes from external data providers. Beyond, it might be the case that not all latent constructs are covered in the dataset.

Summarizing, the choice between the use of primary and secondary data depends on several factors such as research questions and objectives—which is the dominating aspect, but budget, time and other resources as well as the importance of precision of the required data also need to be taken into consideration.

Wrapping up, primary data are collected for a certain research objective while secondary data are existing data collected by other research (teams) that have been acquired for other purposes.

- In the case of ***primary data***, the data basis is a self-collected dataset. This sometimes requires considerable data collection effort, but allows data to be precisely tailored to the research questions and/or hypotheses.

- In the case of ***secondary data***, studies typically make a recourse to existing data sets in order to analyse them again with improved evaluation methods or under new research questions. This reduces survey effort but causes studies to be limited to the existing data.

After having made the decision whether qualitative or quantitative and primary or secondary data is appropriate, market researchers as well as scientific researchers have to decide the way they want to collect the data. This depends, again, on the budget as well as on the research questions. Noteworthy: For all methods, it is important to comply with current data protection regulations. This applies in particular when personal data is collected. The three most common quantitative research approaches are surveys, observations and experiments, which are explained in the following paragraphs:

Survey

In surveys, participants are asked questions on a specific topic (supported or unsupported) in order to obtain information about their opinions, attitudes, preferences, behaviours or demographics. Responses are predominantly given in a highly structured way, e.g. by indicating one's extent of agreement on a predefined scale (e.g. from 1 to 5 or by selecting one of several predefined responses). Nowadays, surveys are usually programmed via online platforms, and the survey link is shared with the participants. Formerly, it was common to do paper and pencil surveys, i.e. use of a printed questionnaire which is more time intensive. Surveys can be conducted in person, by telephone, in writing or online. The choice of method depends on various factors such as the target group, the purpose of the research, the budget and the accessibility of the participants. Having access to a fee-based online consumer panel is the easiest way to collect data within a short period of time and with a good cost-benefit ratio. Further, written surveys, i.e. paper and pencil, usually result in low response rates of less than 15%. Advantages of surveys are obtaining direct and specific information from participants, respectively, consumers or customers. It offers flexibility in formulating questions (supported or unsupported), branching logic as well as random split sampling design. However, disadvantages are that surveys can be prone to response bias, sampling bias or having a not controlled environment, the results can be influenced by factors such as the wording of the questions, the order of the questions or interruptions as well as multitasking of respondents.

Observation

In the observational method, researchers analyse the behaviour of consumers or subjects without direct interaction or questioning. Observation can be covert or overt. In the case of a convert observation, unlike an overt observation, the subject does not have the information that its behaviour is researched. An example for covert observation is a test purchaser whose purpose is to analyse the behaviour of the sales staff. Observations can be conducted in natural settings (e.g. retail stores, restaurants) or in controlled environments (e.g. laboratories). Researchers document the observed behaviour using recordings, notes, videos or other recording methods. Eye tracking is a technical tool that helps, for example, to analyze the direction of gaze and length of time spent in front of supermarket shelves. Maybe the most important advantage of the observation method is that it allows researchers to study behaviour in real situations without the influence of surveys or questionnaires. It provides objective data and can offer insights into unconscious behaviour. In addition, realistic behaviour can be obtained with little bias.

However, observations are usually very time-consuming and require trained staff to collect the data. The interpretation of observed actions can be subjective, and there is a risk that researchers may overlook important contextual information which was not recorded or rather differed among the test subjects, e.g. sounds, temperature or simply the mood of the respondents.

Experiment

Experiments are controlled studies in which researchers manipulate one or more independent variables in order to investigate their effects on a dependent variable. The aim is to identify causal relationships between variables.

Experiments can be conducted in laboratories, test markets or natural settings. Researchers randomly divide participants into one or more experimental groups and a control group and manipulate one or more variables to measure the impact on behaviour. Experiments allow researchers to identify causal relationships between variables and determine cause-and-effect relationships. They offer high internal validity and allow alternative hypotheses to be tested. However, experiments are also often expensive and time-consuming. They can raise ethical concerns, especially when manipulating variables or collecting personal data. Results may not be transferable to real-life situations, especially if the study was conducted in a controlled environment.

Summarizing, the selection of the appropriate research approach depends on various factors such as the research objectives, the research budget, the time available, the accessibility of the participants and the type of variables to be studied. Researchers often combine multiple approaches to gain a more comprehensive understanding and balance the strengths and weaknesses of each method.

36.1.4 Consumer–Citizen-Gap

Decision-making of consumers is of interest when analysing sustainable consumption patterns. However, it is often not possible to get market data, e.g. the real purchase data of specific customers. This can be due to budget limitations, because it is a new product which is not on the market yet or because more specified information is needed, and secondary data does not deliver these. Further, when collecting and analysing survey data and comparing it later on with non-hypothetical data from retail, we generally find a gap in the willingness to pay from survey data and market data. This phenomenon is known as the consumer–citizen gap or attitude-behaviour gap. The consumer–citizen gap represents the discrepancy between the consumers' behaviour as individuals and acting as citizens with a limited budget (Thøgersen 2017). This phenomenon highlights the tendency of consumers to prioritize personal preferences over broader social and environmental concerns and expectations (Vermeir and Verbeke 2006). In the food sector, the consumer–citizen gap manifests itself in various ways. Despite consumers' growing awareness of issues such as climate change and biodiversity loss (de Boer and Aiking 2021), consumers often turn to products that prioritize taste, convenience and affordability over sustainability (Poore and Nemecek 2018). For example, the ongoing demand for produced meat from intensive livestock farming drives deforestation, greenhouse gas emissions and animal welfare concerns, despite the availability of more sustainable alternatives such as higher welfare meat or plant-based proteins. Numerous studies have investigated the factors that contribute to the consumer–citizen gap. Psychological factors such as cognitive biases and bounded rationality play a significant role (Kahneman 2011). Furthermore, many consumers prioritize immediate enjoyment and rely on heuristics rather than thoroughly evaluating the long-term consequences of their decisions (Cohen and Babey 2012). In conclusion, when carrying out hypothetical consumer research, attention needs to be paid to the fact that the willingness-to-pay or the stated intention regarding a certain future behaviour might be overestimated. Figure 36.3 shows the discrepancy between consumers and citizens.

Is there any attitude you have as a citizen that is not reflected in your consumption behaviour? You may think about green energy consumption, sustainable means of transport or seasonal food choices.

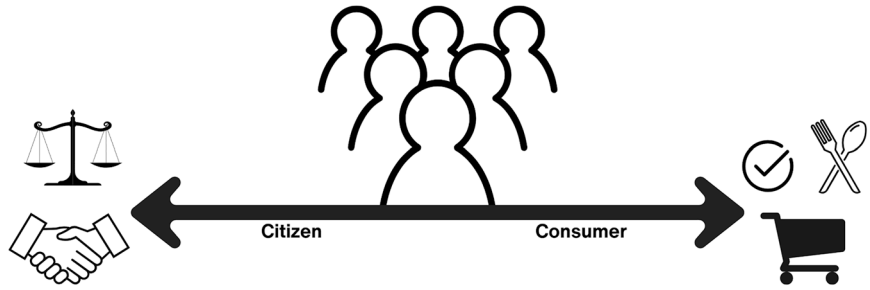


Fig. 36.3 Consumer–citizen-gap

36.2 Encouraging Sustainable Consumer Behaviour in the Bioeconomy

When it comes to sustainable consumption behaviour, there is – besides the various influencing factors on behaviour in general that have been described above – one factor that is particularly important, and that is: how important does a person deem environmental goals or, more broadly, sustainability. The importance of this goal is represented in what we call a person's *environmental attitude*. Sustainable consumption behaviour is on the one hand guided by people's environmental attitude: The more important a person deems environmental protection, the more they will be inclined to act accordingly (e.g. by purchasing sustainable products, saving energy, choosing environmentally friendly modes of transport). On the other side, sustainable behaviour often comes at a cost – for example, sustainable products may cost a price premium, saving energy might require some effort or comfort loss, and environmentally friendly modes of transport may take longer travel times than taking a car. In psychology, such factors that impede the ease of a behaviour are called *behavioural costs* (see ▶ Excursus 36.1). The higher the behavioural costs of a sustainable consumption behaviour, the higher a person's environmental attitude must be for the behaviour to become likely. In the following, we introduce two approaches to encouraging sustainable consumer behaviour, one addressing the behavioural costs and one addressing people's attitudes and values.

36.2.1 Behavioural Costs: Making Sustainable Behaviour Easy

Behavioural costs for consumer purchase, use and disposal behaviour in the bioeconomy can result from different sources such as availability and infrastructure, price structure, information requirements or social influence. Understanding the sources of behavioural costs provides opportunities to tackle and change them, supporting the transition to a bioeconomy in which consumers' needs are well met.

Excursus 36.1 Behavioural costs

Behavioural costs are a characteristic of a goal-directed behaviour (e.g. directed towards environmental protection) that represents the aggregated influence of factors that make the behaviour difficult or effortful. Behavioural costs result from factors in the environment, for example infrastructure, availability, physical features of the setting, market features or social norms. Behavioural costs can be the time, the financial costs or the physical effort that is required to conduct a certain goal-directed (e.g. sustainable) behaviour. Even the threat of social disregard (e.g. when a vegetarian is depreciated at a barbecue party because they refuse to eat meat) and the information effort required for a sustainable behaviour option (e.g. knowing about the source material or ecological benefit of a bio-based product) are types of behavioural costs. Any feature of a behaviour that makes it more effortful in any (even psychological) way is considered a source of behavioural costs.

Availability and Infrastructure

Availability is a main precondition for consumers to choose bioeconomic products. The more widely available (e.g. in supermarkets) bioeconomic products are and the more variety there is (e.g. different brands), the more consumers will encounter and consider such products for themselves. Higher availability increases the likelihood that consumers choose sustainable products (Taube and Vetter 2019). Products that are available only in specialized stores or online platforms have a lower chance of being detected by people who mainly shop sustainable options by occasion instead of intention. For some products, infrastructure is also a critical source of behavioural costs. The use of bio-based methane for cars relies on an infrastructure of gas stations that offer this fuel. The recycling of bio-based plastics (e.g. PLA) requires the respective infrastructure. The composting of biodegradable plastic bags relies on composting plants that meet the required conditions. Consumer behaviour must align with the infrastructure available. The infrastructure available determines how consumers best dispose of products (e.g. whether bioplastic can go to the organic waste stream).

Financial Incentives

More expensive prices of sustainable products, such as bio-based alternatives to conventional fossil-based options are an obvious source of behavioural costs. Thus, financial instruments such as taxes or subsidies can be used to change price structures regarding the relative price differences between sustainable and unsustainable products. For example, some governments incentivize the purchase of electric cars with direct financial contribution to the purchase price. Financial incentives can be effective in helping people overcome first scepticism about novel products by trying them without (financial) risk. A carbon tax is an example that can result in more competitive prices of bioeconomic products compared to fossil-based ones—given that their production is less emission-intensive. Notably, consumers base their decision not merely on price; instead, consumers are willing to pay more for products they prefer on some other dimension (e.g. environmental impact). This, however, requires they have additional information about these potential other advantages.

Information

Information is perhaps one of the core challenges for consumer behaviour in the bioeconomy. Oftentimes, the (biogenic) material source or the biodegradable characteristics of a product are not readily visible. For example, laypeople cannot tell apart different types of plastic packaging materials, e.g. whether it is fossil or bio-based. People are unlikely to prioritize bio-methane if they do not understand its ecological advantages and do not know where to get it. Purchase decision-relevant information can concern the source material of bioeconomic products, for example, that a leather-like material is actually made from fruit peels or fungi. This might be appreciated

if people also understand the ecological advantage, for example, that the production of plant-based leather requires fewer toxic chemicals compared to animal skin-based leather, or that PLA-based plastic is not made from fossil oil but from renewable resources. There is also decision-relevant information about the functionality of bioeconomic product alternatives. Is plant-based leather equally robust as skin-based leather? Is bio-based plastic also safe for food conservation? Lastly, information can also concern the end-of-life treatment of bio-based or biodegradable products. For example, the difference between "biodegradable" and "bio-based" is poorly understood by consumers (Choe et al. 2021). As a consequence, people may wrongly dispose of bio-based material in the organic waste stream, irrespective of its (non-)biodegradability.

Labels that indicate certain characteristics of a product are aimed at promoting trustworthy information to support consumers' decision-making. Labels can inform about the source material (e.g. "vegan" indicating no animal-based ingredients), the ecological soundness (e.g. the "Blauer Engel" label), the biodegradability (e.g. the "seedling" logo) or the appropriate waste stream for disposal (e.g. "packaging", "paper"). Labels are usually provided by a certification body that assesses independently whether a product meets certain specified standards, for example, biodegradability. Labels are thus an attempt to simplify complex information into one visual symbol so this information can be easily detected and processed fast by consumers in a purchase or other decision-making situation. One downside of this simplification may be potential misunderstandings since the full information a label represents (e.g. what exact standards a certain label certifies) is not provided by the mere label depiction but requires further information search and a more general system knowledge (e.g. about the organization of waste and recycling streams and technologies). This effort is most likely only exerted by people who are rather interested and motivated to learn about their environmental impact (see ▶ Sect. 36.2.2 below). Another downside is information overload as there are various labels and a lot of further information on most products–so it is questionable whether yet another label is a real relief for overwhelmed consumers.

Social Influence

People tend to align their behaviour with social norms, that is, their belief what others do or consider appropriate to do in a certain situation. Accordingly, acting against social norms or expectations can be psychologically stressful. It bears the risk of being ridiculed, offended or excluded by others for norm-deviant behaviour. This is threatening for most people, and therefore people try to avoid such behaviour and conform with social norms instead. Purchasing or using products that are novel or "unnormal" can thus come at certain social costs when consumers are unsure whether others will approve of them. Conversely, social influence can also be used to decrease behavioural costs of sustainable consumer behaviour. For example, some individuals serve as role models for others (e.g. celebrities, organizational leaders, people with high status). Role models can promote sustainable consumption behaviours or bioeconomic principles and thus lower social costs of the respective behaviours. Very strong social influence also comes from close people, such as family members or friends. When consumers experience that someone close uses and trusts a novel product (e.g. plant-based leather shoes), they are more likely to also show such behaviour and try out a new product. Lastly, social influence can also impact societal processes. Many sustainable behaviours—for example, consuming bioeconomic products—can feel ineffective as an individual contribution to solving environmental problems. If people, however, experience that many others are doing the same and the joint effort has an impact, they feel collective efficacy. Collective efficacy beliefs have been shown to be motivating for individual sustainable behaviour (Fritsche et al. 2017). Thus, social processes such as establishing shared norms, role model behaviour or collective efficacy can be effective approaches to decrease behavioural costs of sustainable behaviour.

Summary of Behavioural Costs as a Way to Encourage Sustainable Consumer Behaviour

One approach of strategies to encouraging consumer behaviour in support of a transition to a bioeconomy is thus via taking the behavioural cost into account. Providing necessary and easy-to-use infrastructure, increasing the availability and designing an attractive price structure (e.g. via subsidies or incentives) can be effective ways to make sustainable consumption behaviours easier – and by that more likely. Beyond these rather obvious factors, the self-determined consumer can also be guided by information provision that helps their decision processes – especially environmentally conscious consumers are likely to consider information about environmental benefits of bioeconomic products in their choices. Supporting the development of new social norms and making use of social processes (such as the influence of role models and peers on others) is also a promising way to make sustainable consumer behaviour easier and thus more likely for people.

36.2.2 Attitudes and Values: Person-Intrinsic Drivers to Overcome Behavioural Costs

Since the consumption behaviour in a bioeconomy (including purchase, use and disposal of products) comes with varying behavioural costs, people need a reason to be willing to overcome them. The reason why people engage in *sustainable* consumption behaviours is that they aim to protect the environment (Kaiser and Wilson 2004). It depends on people's attitudes and values whether they deem environmental protection and sustainability important (Note that the same can be true for other important goals, e.g. health: the reason to engage in health-supportive behaviours is that a person finds this goal important. Also, one behaviour can serve several goals, e.g. health *and* environmental protection). Value orientations that transcend the self (rather than put self-enhancement at the centre) are associated with more willingness to engage in sustainable consumption practices. Self-transcendent values place the welfare and well-being of other people, other species and nature itself at the centre of one's personal evaluation of what is good or bad and what is the right thing to do (Schwartz 2012). Values are representations of desirable goals that serve as guiding principles in one's life (Schwartz 1992) and they are the basis on which people develop their attitudes towards specific or abstract objects, events, topics, people, etc. Environmental attitude is people's evaluation of environmental protection and is therefore closely related to universal and biospheric values. In the theory on environmental attitude (see e.g. Kaiser et al. 2010), the extent to which people engage in environmentally friendly behaviours is an indicator of their environmental attitude strength. The relationship is as follows: a person with a low level of environmental attitude (that is, someone who deems environmental protection not very important) will be somewhat likely to engage in such environmentally friendly behaviours that come at rather low behavioural costs (e.g. separating their waste, reusing their shopping bags). However, this person is rather unlikely to engage in higher-cost environmental behaviour such as abstaining from car use or following a plant-based diet. A different person with a high level of environmental attitude is likely to also overcome higher behavioural costs and thus engage in more demanding sustainable behaviours, additionally to the low-cost behaviours. Environmental attitude can thus be regarded as the person-intrinsic motivational resource that enables people to engage in increasingly demanding (that is, higher behavioural cost) behaviours that serve the goal of environmental protection. Accordingly, fostering people's environmental attitude has a general effect on sustainable behaviours: irrespective of the specific behaviour, any behaviour that supports environmental protection (or sustainability as a goal) becomes more likely as people's environmental attitude increases. Promoting sustainability as a societal and socially shared goal as well as nurturing bio-

spheric and cooperative values (instead of self-enhancement and egoistic values), provides a promising basis for people to collectively develop stronger environmental attitudes and align more of their consumption practices with these goals and values.

36.3 The Food Retail Sector

Consumers are confronted with food choice in everyday life. Thus, in the following section, we will shed light on the middle of the food value chain—retail. To change consumers' food consumption behaviour, it is especially important to closely examine the point of sale where decision-making takes place: supermarket shelves. The food retail sector plays a crucial role within the food value chain, as it connects food and beverage producers with end consumers. In establishing more sustainable consumption patterns, retail is a key player. It comprises the businesses where consumers can buy food products for consumption outside the store, mainly at home, with the exception of takeaway restaurants (e.g. Çakir et al. 2020). Food retail systems differ significantly between different geographical regions, e.g. between the Global North and the Global South (Richards and Pasirayi 2023), but also within high-income regions such as the EU and the United States (e.g. Çakir et al. 2020). For example, the food retail sector in many developing countries is still undergoing a transformation process with an increasing penetration of modern retail formats such as supermarkets or hypermarkets (Richards and Pasirayi 2023). This section therefore, focuses on food retail in industrialized countries with a focus on the EU. Besides some direct sales or sales through smaller specialized grocery stores (e.g. Banterle et al. 2009), the food retail sector is the largest sales channel for food and beverage manufacturers (DBV 2024). At the EU level, the sector comprises around 750,000 enterprises (Eurostat 2024), with more than 90 per cent of these companies being small and medium sized with less than 250 persons employed (Eurostat 2023). With around 6.3 million employees and a turnover of around €1.14 trillion, food retail is an important pillar of the European economy (Eurostat 2024).

According to the European Commission's classification, the sector can be classified into "Retail sale in non-specialized stores with food, beverages or tobacco predominating" and "Retail sale of food, beverages and tobacco in specialized stores" (Eurostat 2008). While the former section includes several well-known food retail chains with their supermarkets and larger hypermarkets such as Tesco (UK), the Schwarz group (including Lidl), Rewe and ALDI (Germany) or Carrefour and E.Leclerc (France) (Lebensmittelzeitung 2023), the latter section of specialized stores includes a very large number of lesser-known regionally active retail chains or smaller specialist stores that focus on a specific food category, such as bakeries, butchers, greengrocers or beverage retailers (Eurostat 2023). This results in the large number of 750.000 food retail companies in the EU, although usually only a handful of well-known chains come to mind when thinking about food retailing. The dominance of these large retail chains has implications for consumers and upstream food processors, some of which are highlighted below.

> The ***food retail sector*** is central to the food value chain as it connects food and beverage producers and end consumers. It includes those businesses where consumers can buy food products to consume outside the store, mainly at home (excluding takeaway restaurants) (e.g. Çakir et al. 2020). The food retail sector is composed of a heterogenous group of businesses, including both larger non-specialized stores with a wide range of food products and smaller, specialized stores focusing on specific food items such as bakery products, beverages, meat or greengrocers (Eurostat 2008, 2023).

Food retailers play an important role in the food value chain, as they enable the effi-

cient distribution of food products from producers to the end consumer. This creates significant added value for both food and beverage processors and consumers. For the latter, this means larger variety of products, reduced prices and increased convenience, among other benefits (Richards and Pasirayi 2023; Bronnenberg and Ellickson 2015). In addition, food retailers have an important function in satisfying consumer demand by offering an extensive product selection which matches consumers' preferences and budgets (Richards and Pasirayi 2023). In doing so, food retailers must constantly adapt to changing consumer demands, for example, with respect to convenience or sustainability (DBV 2024). Given their powerful position in the food value chain (e.g. Sexton and Xia 2018) they also have an important role to play in fulfilling commitments under the EU's Farm to Fork Strategy. This includes the reformulation of products to increase their nutritional value or improving their environmental footprint, as well as shaping consumers' dietary habits (Eurostat 2023; European Commission 2020).

Table 36.1 EU's largest food retail groups in 2023

Retail chain	Country	Gross turnover (Bn. €)
1. Schwarz Group	Germany	172.24
2. Rewe Group	Germany	90.92
3. ALDI	Germany	85.29
4. Tesco	United Kingdom	77.31
5. Carrefour	France	76.00
6. EDEKA	Germany	75.40
7. E.Leclerc	France	51.59
8. ITM Intermarché	France	39.11
9. Auchan	France	38.26
10. Sainsbury's	United Kingdom	38.18
11. Ahold Delhaize	Netherlands	37.99
12. Mercadona	Spain	34.41
13. Metro	Germany	34.31
14. Asda	United Kingdom	29.49
15. Système U	France	29.26
16. Jerónimo Martins	Portugal	28.63
17. Coop	Switzerland	28.35
18. Migros	Switzerland	25.87
19. Conad	Italy	24.84
20. SPAR	Austria	21.64

Source: own illustration based on Lebensmittelzeitung (2023)
Including United Kingdom and Switzerland

36.3.1 Key Actors and Market Structure

Despite the large number of retail companies in the EU mentioned above (750,000), the sector is characterized in many countries by a few large and well-known retail chains that are responsible for the majority of food and beverage sales within the country. Table 36.1 shows the twenty largest food retail groups in the EU, which operate a variety of full-line and discount chains. The retail groups are listed according to their gross turnover in 2023. It can be observed that three of the five largest retail groups in the EU are German companies. The ranking is led by the Schwarz Group, followed by the Rewe Group and ALDI. The United Kingdom company Tesco and the French Carrefour group complete the Top 5 (Lebensmittelzeitung 2023). It is also worth mentioning that the Schwarz Group and ALDI are also represented in the top 10 list of the world's largest food retailers, which is led by a wide margin by Walmart (USA), whose turnover in 2023 amounts to €590 Bn. (Statista 2023, 2024).

In most EU countries, these large chains control the food retail sector, as they account for a significant share of total food retail sales. The degree of this dominance can be measured by the concentration ratio, which indicates the percentage of total retail sales accounted for by the few large companies. Accordingly, the concentration ratios in most EU countries are very high. For example, the five-firm concentration ratio i.e. the percentage share of the five largest food retail chains in overall food retail sales, exceeds 70% in most EU countries (see e.g. European Commission 2016, p. 44, based on Planet Retail data). For example, in Germany the four largest players regarding turnover EDEKA, the Schwarz-Group, ALDI and the Rewe Group, are responsible for 76% of total retail sales (Lebensmittelzeitung 2023a; Lebensmittelpraxis 2024). This means that food retailing in most EU countries is dominated by a small number of large companies—an industry structure known as an oligopoly.

> The ***concentration of an economic sector*** refers to the turnover achieved by the ususally four or five largest companies in the sector compared to the sector's total turnover. There are several indicators for measuring concentration of a sector, with the four or fivefirm concentration ratio being the most commonly used in official statistics. The five-firm concentration ratio, for example, is calculated as the sum of the turnover of the five largest companies in the sector divided by the total turnover of the sector. A concentration ratio close to 0indicates high competition, while high values (around 0.7) indicate oligopolistic market structures and low competition. Cartel authorities use concentration ratios, for example, to assess the effect of mergers and acquisitions on the strength of competition in an industry.

From an economic perspective, high concentration can lead to inefficiencies in the food value chain and have consequences from a competitive perspective due to the market power it can bring. For example, research has shown that high concentration and oligopolistic market structures in food retailing can have a negative impact on small and medium-sized food processors, farmers and consumers (Sexton and Xia 2018). In this context, the retail sector has recently been under frequent scrutiny by cartel authorities for possible abuse of its negotiation power and unfair trading practices towards food processors and farmers. This includes a detailed assessment of possible mergers and acquisitions that could further increase concentration (e.g. Hirsch et al. 2021; Koppenberg 2023; Lebensmittelzeitung 2014, 2024; European Commission 2024). Examples are the investigation of possible collusion between French retailers Casino and Intermarché in 2019 (European Commission 2019) or the takeover of the insolvent Kaiser's Tengelmann stores by EDEKA and Rewe, which was only approved after a detailed assessment of the effects on

competition and several rounds of legal discussions (Lebensmittelzeitung 2015; Wirtschaftswoche 2017).

36.3.2 Current Developments in Food Retailing

Due to the Covid-19 pandemic and the war in Ukraine, prices for agricultural products have risen significantly in recent years (Acharya et al. 2023). These price increases are passed on within the food value chain, with several fierce "price fights" between major retailers and producers. Retailers have accused producers of going too far with their price increases, resulting in certain products being temporarily delisted from retailers' shelves. Two of the many examples are the removal of Pepsico products by the French retailer Carrefour in early 2024 and a delivery stop of Procter & Gamble products for EDEKA in 2022. This has temporarily led to empty shelves in individual supermarkets of European retail chains (Lebensmittelzeitung 2023b; Reuters 2024). However, despite the recent price increases, food prices in many EU countries have been relatively low from a consumer perspective. While the high concentration in food retailing leads to upstream market power i.e. towards producers and farmers, there is strong price competition between the large food retailers at the downstream level i.e. towards consumers, which leads to relatively low food prices. This high price competition is intensified by the presence of food discounters, the high share of retailers' own brands, and the relatively low share of food in total consumer spending (Wirtschaftswoche 2016). For example, a significant price reduction by the discounter Lidl in the vegan products category in 2022 led to a relatively quick response by ALDI to also decrease prices in this category (Lebensmittelzeitung 2023c). The retail sector is subject to ongoing developments, particularly in terms of digital transformation and changing consumer preferences. Examples of recent developments include the growth in food e-commerce, which has been boosted by the Covid-19 pandemic, and the introduction of checkout-less supermarkets based on "Just Walk Out" technologies, initiated by Amazon with its Amazon Go stores. As this can reduce shopping time and increase convenience, several traditional chains are following suit and opening their own alternatives. Examples from the UK include "Getgo" by Tesco and Sainsbury with "Pick & Go", "Rewe Pick & Go" in Germany or French retailer Carrefour with "Carrefour Flash" (Lebensmittelzeitung 2022). It is also to be expected that further developments in the areas of digitalization, artificial intelligence and data analytics will shape the food retail sector in the future.

Questions

1. Why is consumer behaviour relevant for the bioeconomy?
2. According to Kotler et al. (2019), what factors influence consumer behaviour. Provide examples for each category?
3. What is the consumer-citizen gap and why does it impact consumer behaviour in the bioeconomy?
4. What is a typical feature of the structure of food retailing in many European countries and why is this structure often viewed critically by food and beverage producers, farmers and cartel authorities?

Answers

1. Consumer behaviour is crucial for the success of the bioeconomy because consumers directly influence market dynamics through their purchasing decisions, usage and disposal behaviours. Sustainable products from the bioeconomy often come with a price premium, and their market success largely depends on consumers' willingness to pay this extra cost. To ensure these products are embraced, it's essential to understand how consumers perceive their environmental benefits, functionality and overall value. Additionally, consumer behaviour affects the entire life cycle of

products, especially during the usage and disposal phases, which can account for a significant portion of their ecological impact. Misunderstandings, such as confusing "biodegradable" with "home-compostable", can lead to improper disposal and reduce the intended environmental benefits. Furthermore, consumer demand can drive innovation by encouraging companies to develop more sustainable products and technologies, thereby fostering the transition to a bioeconomy. Therefore, understanding consumer behaviour helps shape products, marketing strategies and the overall success of the bioeconomy.

2. According to Kotler et al. (2019) factors that influence consumer behavior include:
   - Cultural factors: Cultural values, beliefs and social class. For example, different cultures may have unique preferences, and people from different social classes may have varying buying habits.
   - Social factors: Peer groups and family. For instance, a person may be influenced by their family's preferences or by the opinions of celebrities or colleagues.
   - Personal factors: Age and profession. For example, a young professional might prioritize technology gadgets, while older consumers may focus on comfort and reliability in products.
   - Psychological factors: Perception and motivation. An example is how a consumer's previous experiences with a brand or product can shape their perception, or how their motivation to fulfill basic needs (e.g. food and shelter) influences their purchasing decisions.
3. The consumer-citizen gap refers to the difference between individuals' attitudes and intentions as consumers versus their behaviours as citizens with limited budgets. This gap is particularly relevant in the bioeconomy because it highlights the discrepancy between consumers' expressed concern for sustainability and their actual purchasing decisions. Consumers may claim to care about environmental issues, such as climate change and biodiversity loss, but when it comes to making real-world choices, they often prioritize personal preferences like taste, convenience and cost over sustainable alternatives. For example, despite being aware of the negative impacts of intensive livestock farming, consumers often continue to buy cheaper, less sustainable meat options. This gap impacts the bioeconomy by creating a disconnect between consumers' willingness to support sustainable products in theory and their actual buying behaviours, which can hinder the adoption of more sustainable bio-based products. Factors like cognitive biases, bounded rationality and a tendency to prioritize immediate gratification over long-term environmental impacts contribute to this gap, making it challenging for sustainable bioeconomy products to gain traction in the market.
4. The food retail sector in many EU countries is characterized by a high degree of concentration. For example, the five-firm concentration ratio is over 70% in many countries. As high retail concentration is associated with power imbalances in the food value chain and potentially unfair trading practices towards farmers and processors, the food retail sector is closely observed by antitrust authorities in many EU countries.

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Inter- and Transdisciplinary Research in Bioeconomy

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Fig. 37.0 Inter- and Transdisciplinary Research in Bioeconomy. (© Universität Hohenheim, Max Kovalenko) (▶ https://doi.org/10.1007/000-hvj)

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The concept of the Bioeconomy addresses complex societal issues where multiple dimensions are in conflict, and a range of scientific and practical knowledge is required to find solutions. This chapter sets out definitions, principles and tools for conducting inter- and transdisciplinary research in the context of bioeconomy. Our objective is to provide readers with a comprehensive understanding of inter- and transdisciplinary research approaches and to equip them with the concepts, skills and instruments required for the design, planning, implementation and evaluation of such research. Our disciplinary background in social sciences in agriculture guides our approach towards the bioeconomy, including the presentation of case studies, utilisation of concepts, methodologies and tools. In the sections of this chapter, we focus on the justification of inter- and transdisciplinary research in the bioeconomy (► Sect. 37.1), on the characteristics of the inter- and transdisciplinary research process (► Sect. 37.2) and on methods and tools to make collaboration effective and efficient (► Sect. 37.3). Finally, we highlight particularly the roles, responsibilities and agencies that researchers have when engaging in inter- and transdisciplinary research (► Sect. 37.4).

Learning Objectives

After studying this chapter, you will…

- …be able to describe the role and potential of inter- and transdisciplinary research approaches in shaping bioeconomy strategies and related transformation (see ► Sect. 37.1).
- …be able to identify and explain the conceptual bases, principles and phases of a transdisciplinary research process and the integration of different types of knowledge (see ► Sect. 37.2).
- …be able to give examples of methods and tools that support effective co-design, implementation and assessment of inter- and transdisciplinary research projects and the co-production of knowledge (see ► Sect. 37.3).
- …be able to evaluate the role and agency of research in multi-actor research project collaborations (see ► Sect. 37.4).

37.1 Why Utilise Inter- and Transdisciplinary Research in the Bioeconomy?

During the early 2000s, bioeconomy strategies became a widespread component of national politics in Western countries and alliances (BMEL 2014; EC 2012; OECD 2009). Underlying concepts highlighted the potential that bioeconomy approaches bear for the national economies, the sustainable management of natural resources and the well-being of citizens, but comparative studies also revealed differences with respect to underlying concepts, scientific argumentation and political justification (Staffas et al. 2013; see also ► Chap. 2). Since then, the acceptance of bioeconomy concepts as performant discourses has widely increased, and the scientific and political understanding and use of the bioeconomy term have been continuously broadened by integrating it with e.g., system thinking (Wensing et al. 2021; Vargas-Carpintero et al. 2022), circularity (Harder et al. 2021; Schipfer et al. 2024) or food system approaches (Canales and Fears 2023). Still, what remains common within these manifold understandings and interpretations is that a strong emphasis is given to their scientific grounding and, in this respect, to the necessity of applying inter- and transdisciplinary approaches.

Within a social sciences' perspective, bioeconomy can be understood as a policy discourse (see ► Excursus 37.1) that selects and defines societal problems through problem framing and creates a 'performative narrative', i.e. a convincing story that offers solutions. Bioeconomy discourses combine various problem streams; they usually claim to address complex societal problems and challenges in which environmental, economic and social dimensions are dynamically interwoven in both, conflictive or mutually enhancing manners. In the literature, such challenges are often referred to as 'wicked problems' (Batie 2008), highlighting their complexity and resistance to straightforward solutions. For example, transitioning from fossil-based to renewable materials is not just

a technological shift but also involves changes in institutional structures, consumption patterns and the underlying mental frameworks and social norms that shape these behaviours.

Excursus 37.1 Discourses

'Discourse' has originally been used as a concept for sequential analysis of the flow of conversations. Then, the concept was interpreted in a broader sense by the work of Michel Foucault (a French philosopher, 1926–1984), who defined discourse as 'systems of thoughts composed of ideas, attitudes, courses of action, beliefs and practices that systematically construct the subjects and the worlds of which they speak'. Foucault traced the role of discourses in wider social processes of legitimisation and power, emphasising the construction of current truths, how they are maintained and what power relations they carry with them. Foucault argued that discourse is a medium through which power relations produce speaking subjects, and it can be seen as a practice through which power structures are reproduced. Thus, power and knowledge are inter-related, and therefore every human relationship is a struggle and negotiation of power. Foucault's analysis has inspired discourse analysis in many fields, and it has become an integral part of political analysis in particular through the work of Maarten Hajer (a Dutch political scientist). He defined a policy discourse as ensemble of ideas, concepts and categories through which meaning is given to social and physical phenomena. It is produced and reproduced through an identifiable set of practices. In a policy arena, different competing policy discourses may be identified. A policy discourse is produced and maintained by a discourse coalition, a group of actors that, in the context of an identifiable set of practices, shares the usage of a particular set of story lines over a particular period of time (Foucault 1981; Hajer 1995).

37.1.1 What Makes Problems Wicked?

The process of designing and implementing a bioeconomy strategy is, therefore, not just about technological innovation to overcome particular challenges; it is a transition process, a process of social change within societies (Geels 2002), that starts from so-called wicked problems (see ▶ Sect. 38.1). Such a transition process is targeted to voluntarily change individual and collective behaviours, as well as respective practices of individual and collective actors through the enhancement of problem-solving and innovation adoption and diffusion processes. How can we understand and determine this 'wickedness' of problems?

Essentially, a problem shall be conceived as the perceived discrepancy between a desired and an actual state in which no routinized solution exists (Hoffmann et al. 2009:63). This definition or 'basic structure' holds true for both, individually as well as collectively determined problems, so the level of problem allocation in principle does not matter. Looking deeper into the definition, the challenge for addressing problems comes with the premise that they are constructed by the problem owner(s) and thus depend on perceptions, values, experiences and knowledge, which are personal and subjective. Consequently, every element of the structure requires in-depth consideration and can be the object of questions, discussions and divergences. In cases where no easy agreement on these elements can be reached among the various actors concerned with and engaged in the problem topic, and where there is a lack of certainty about what the problem and the solution are, we consider it to be a complex or wicked one (Batie 2008; see ◘ Fig. 37.1).



Fig. 37.1 Basic Structure of a wicked Problem. (Adapted from Hoffmann et al. 2009)

Excursus 37.2 Example of a Complex or Wicked Problem in the Bioeconomy

In the early 2000s, transport biofuels particularly in the EU and the USA were perceived as a sustainable solution to broad complex challenges, including climate change, dependence on fossil fuels, weakening energy security, as well as job insecurity in the agricultural sector. Over the past decade, policymakers' perceptions of transport biofuels shifted from a win-win solution to a major challenge in planning for renewable energy transitions. In the course of biofuel production development, there were unforeseen side effects of biofuels on the environment, health, food security, land use, grain markets, as well as smallholders' rights (Fast and McCormick 2012). As biofuels now have become widely integrated in national policies, as being a solution to other complex problems, it is impossible to indicate the ending point of biofuels. This confusion between a cause and a symptom and between a solution and a problem is another wicked problem characteristic, which illustrates that wicked problems cannot be permanently solved (Rittel and Webber 1973). Continuous solutions are needed to address the uncertain conditions.

In order to disentangle and address complex problems, systems thinking has proven its usefulness as it is a meta-theoretical approach that seeks to depart from linear thinking in order to model complexity. Initially, it extends the model of simple causation (cause–effect) by introducing feedback loops (reciprocity) and linkages to other entities. Feedback loops and linkages between several elements are necessary but not sufficient to characterise a group of elements as systems. In systems, the elements interact in ways that new collective patterns and regularities emerge such that larger entities hold properties the individual elements do not exhibit ('the system is more than the sum of its parts') (Schiere et al. 2004) (also see ▶ Sect. 3.5), a phenomenon, which is usually referred to as 'emergence'.

Systems theory is a powerful and extremely productive conceptual approach in the sense that it sets manifold impulses for the creation of linkages and the integration of knowledge stemming from various disciplines and groups of professional actors. Thus, making use of systems thinking enhances substantial exchanges about cause-effect and interdependent, multi-directional relationships and linkages. By this, system thinking supports targeted analytical approaches to address and work on holistic, overarching challenges and complex problems. Hence, systems thinking is considered as a very practical ingredient to bioeconomy-related research and transformation (Wensing et al. 2021).

37.1.2 Definitions of Inter- and Transdisciplinary Research

In order to appropriately address complex problems, bioeconomy-related research frequently adopts inter- or transdisciplinary approaches, which means researchers from various disciplines and possibly also people with a practical professional background work together towards the development and imple-

mentation of solutions (Hirsch Hadorn et al. 2008; Friedrich et al. 2021). Although there is widespread acceptance that inter- and transdisciplinary research approaches are key for solving real-life, complex problems (Batie 2008), there is still divergence with respect to the understanding of the terms in the literature. We, therefore, outline a widely shared understanding of the terms 'multi-disciplinarity', 'interdisciplinarity' and 'transdisciplinarity'.

Doing joint research as a group of researchers with different disciplinary backgrounds is usually denoted as 'multidisciplinary'. *Multidisciplinarity* refers to research that addresses a question or an issue from a variety of disciplinary perspectives, without purposefully integrating the various findings. Results of this type of research usually consist of added disciplinary pieces without synergies rather than a connected composition (Pohl and Hirsch Hadorn 2008). As an example, we see that in the policy strategy 'Innovating for Sustainable Growth: A Bioeconomy for Europe' (2012), the EU develops twelve crucial actions among which one is 'increasing cross-sectoral and multi-disciplinary research and innovation' (EC 2012).

Interdisciplinarity involves different disciplinary approaches to research in a conceptually coordinated way, where the disciplinarily guiding assumptions and research concepts ('worldviews') are made explicit and mutually connected. Thus, interdisciplinarity implies overcoming classical boundaries and reorganising scientific questions and knowledge (Mittelstraß 1987). With an interdisciplinary approach, 'facts and findings' from each discipline are critically evaluated in light of the 'facts' from the other disciplines, and the attempt is made to integrate discipline-specific knowledge into a larger whole (Schmidt 2008). The broader the range of disciplines involved, and especially if both natural and social sciences' researchers participate, the more challenging this step of knowledge integration is.

Finally, *transdisciplinarity* broadens the scope of research into another study dimension. Besides the orientation towards real-life problems, this approach also seeks to integrate lay or non-academic knowledge with scientific one. This understanding is expressed in the definition of Lang et al. (2012, p 27), where 'transdisciplinarity is a reflexive, integrative, method-driven scientific principle aiming at the solution or transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge'. Thus, the interface between society and science is a key constituent of transdisciplinarity, which implies not only the necessity to create mutual understandings but to go further towards interaction and collaboration among the various actors.

In summary, interdisciplinary research focuses on integrating knowledge across disciplines and can vary in scope, from involving disciplines with compatible methods and epistemologies to bridging completely disparate disciplines. Transdisciplinary research aims to go beyond, by transcending disciplinary worldviews to include non-academic perspectives and expertise from various stakeholders (Pohl et al. 2021).

> ***Multidisciplinarity*** refers to research that addresses a question or an issue from a variety of disciplinary perspectives, without purposefully integrating the various findings.

> ***Interdisciplinarity*** involves different disciplinary approaches to research in a conceptually coordinated way where the disciplinarily guiding assumptions and research concepts ('worldviews') are made explicit and mutually connected.

> ***Transdisciplinarity*** "is a reflexive, integrative, method-driven scientific principle aiming at the solution or transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge" (Lang et al. 2012, p 27).

There is no specific definition of inter- and transdisciplinarity concepts in the bioeconomy context; we, therefore, encourage readers to engage with the concepts and to adopt a pragmatic approach rather than to stick to definitions. Secondly, as inter- and transdisciplinary research practices share several core components, such as the integrative design of the research, the team collaboration of the involved actors, the joint conception of the research problem and the necessity of integrating and synthetizing knowledge from various disciplines and sources (Jahn et al. 2012; Zscheischler and Rogga 2015), we will mostly address them jointly in the following sections.

37.2 Inter- and Transdisciplinary Research as a Process

As mentioned in the previous section, both inter- and transdisciplinary research approaches are part of a broader discourse of boundary crossing that seeks to overcome the limitations of single-discipline studies by integrating multiple sources of knowledge (Pohl et al. 2021). In the case of interdisciplinary research, the integration is between different academic disciplines, bringing together various perspectives to create a more comprehensive understanding of complex issues. Transdisciplinary research, on the other hand, includes this interdisciplinary integration but goes even further by actively incorporating non-academic perspectives, such as those from practitioners, policymakers and local communities into the research process. According to Mitchell et al. (2015), transdisciplinary research is distinguished by its emphasis on contributing to three specific outcome spaces: (1) tangible improvements in the real-world context, which may include changes in policies, practices or strategies, (2) production and dissemination of knowledge that is accessible and useful to a wide range of audiences and disciplines, (3) mutual and transformative learning for both researchers and practitioners, leading to changes in practices and perspectives.

To understand inter- and transdisciplinary research as a collaborative process, we introduce the model that was developed by Lang et al. (2012), which outlines three key stages of a transdisciplinary research process (see Fig. 37.2):

- The problem framing and team building phase
- The co-creation of solution-oriented transferable knowledge phase
- The (re-)integration and application of created knowledge phase.

Although this model was specifically developed for transdisciplinary research, it is equally relevant for interdisciplinary research as both approaches share the need for structured collaboration across different fields of knowledge, as the structuring of phases provides a valuable guide for navigating the process. In the following, we highlight what needs to be done and achieved in each of the phases, and thereby, focus on the key components and principles.

37.2.1 The Problem Framing and Team Building Phase

By its very definition, inter- and transdisciplinary research starts with the perception of a (somewhat) complex real-life problem. How this problem is framed and structured becomes the keystone of the research process, because it implies making crucial decisions about which aspects of the problem to include and which relevant disciplines and, in the case of transdisciplinary research, which non-academic actors to involve. These decisions significantly influence whether and how the project will achieve its desired impact (Pohl and Hadorn 2007).

37.2.1.1 Problem Framing

In interdisciplinary research, the focus is on integrating different academic disciplines to create a more comprehensive understanding of the problem. The problem framing process remains primarily within the academic realm, relying on the expertise of various dis-

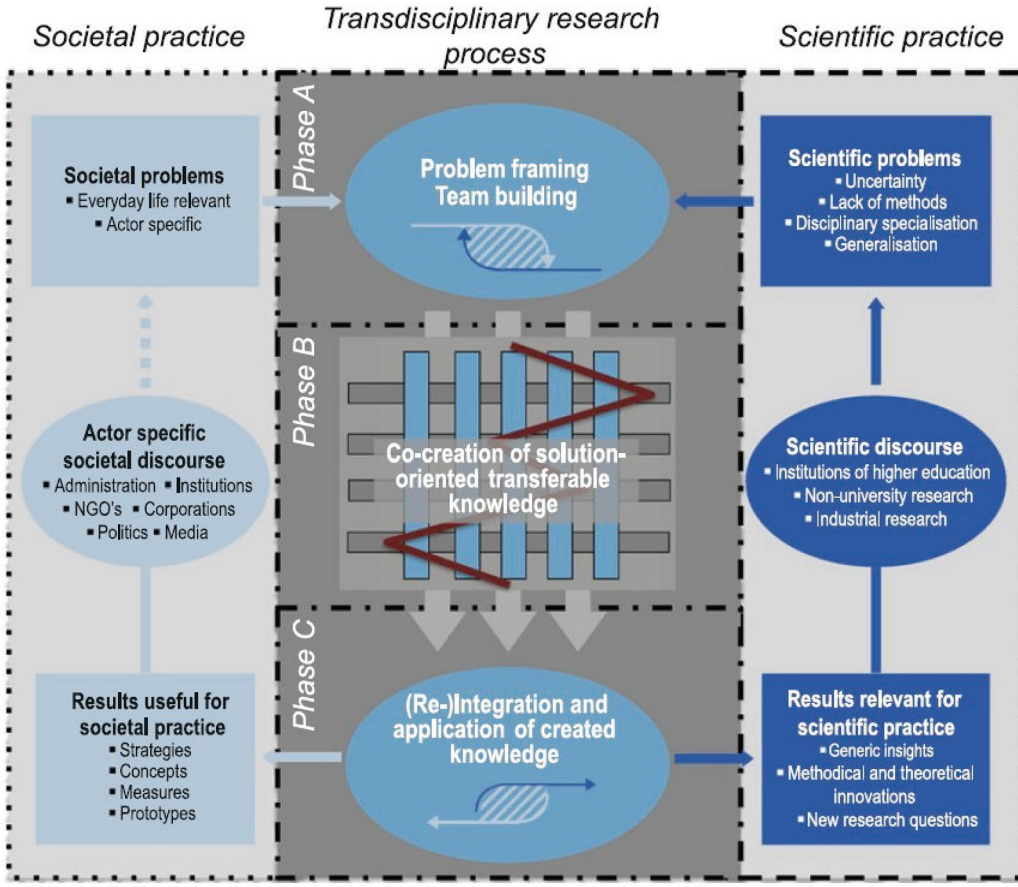


Fig. 37.2 Conceptual model of an ideal-typical transdisciplinary research process (Lang et al. 2012, p 28)

ciplines to refine the problem's scope and approach. The scope of interdisciplinary research can vary, ranging from narrow integrations, where disciplines with compatible methods and epistemologies collaborate, to broader efforts that involve bridging disparate approaches and methodologies (Pohl et al. 2021). The recursive nature of this process ensures that, as new academic perspectives are brought in, the problem framing is reassessed and refined to better address the complexity of the problem.

Transdisciplinary research, on the other hand, extends this process beyond academic boundaries by actively involving non-academic actors. In this context, the problem framing process is even more dynamic and recursive. Initially, a preliminary perception of the problem guides the identification of relevant disciplines and non-academic actors. As these actors contribute their perspectives, the problem perception is reassessed and further refined, often leading to a broader and more nuanced understanding of the problem at hand (see example of recursive problem framing below for illustration).

As was elaborated earlier, transdisciplinary research is motivated by real-life problems and thus may be induced by any type of actor concerned with it. Nevertheless, in practice, transdisciplinary research is frequently driven by third-party funded programmes, which means researchers are often the primary initiators. In these cases, the identification and integration of non-academic actors is a key step in the first phase. It comes with the challenge of engaging with people from different professional and societal backgrounds, which implies e.g., overcoming communication gaps and intercultural divides.

► Example: Recursive Problem Framing

Consider a bioeconomy project focused on assessing whether and under which conditions agriculture can provide raw materials for the construction sector. Initially, agronomists, farm economists and farmers might be involved if the challenge is primarily within the agricultural production sphere. They would define the problem based on their expertise, focusing on aspects such as crop yield, soil health and economic viability for farmers.

However, as the problem is further explored, it becomes evident that technological processes for integrating new materials into construction are also critical. At this point, construction engineers and material processing experts are brought in. Their input shifts the focus to issues like material compatibility, structural integrity and technological feasibility, leading to a broader and more detailed problem framing.

Furthermore, as potential market responses and economic impacts are considered, marketing experts and potential consumers are included. Their perspectives might highlight additional factors such as consumer acceptance, market trends and economic incentives. This iterative inclusion of new actors and perspectives continues to refine and expand the problem definition, ensuring a comprehensive understanding that encompasses all relevant dimensions. ◄

37.2.1.2 Establishing Effective Collaboration

Identifying and understanding actors according to their interest and influence is particularly crucial in transdisciplinary research. This activity typically involves grouping actors based on (i) problem ownership, (ii) on their interest in outcomes and (iii) on their ability to act and to influence and shape project outcomes. Thus, actor identification in transdisciplinary research necessitates both an understanding of the research question, so that boundaries of the social and ecological system can be established, and an overview of required resources, rights and capabilities to successfully complete the project. It is an iterative process, where stakeholders might be added as the analysis continues. In practice, it is often not possible to identify all concerned stakeholders, and it is necessary to draw a line at some point, based on pre-determined and well-defined decision criteria, in order to stop the selection and recruitment process (Gerster-Bentaya 2015; Grimble and Wellard 1997).

Once the relevant actors have been identified, the next critical challenge in inter- and transdisciplinary research is establishing effective collaboration among the group of actors, transforming them into a cohesive team capable of working together. This process involves addressing key questions such as: How will the group balance both individual and collective performance to ensure that the expertise of all actors is fully utilised? How will decisions be made regarding what exactly will be studied, and how the research will be conducted? What will be the specific responsibilities and tasks of the various actors, and how will the results be determined and evaluated? Such questions are frequently treated as a black box in publications on inter- and transdisciplinary research (Zscheischler and Rogga 2015); they can and should, however, be addressed explicitly, e.g., based on sociological and socio-psychological concepts, for the sake of methodological transparency (Knierim et al. 2021).

Besides, in transdisciplinary research, the integration of diverse non-academic actors adds additional layers of complexity, necessitating further considerations such as: How will the team navigate the different languages, values and priorities of academic and non-academic actors? How can the varied expertise and knowledge systems of the diverse actors be integrated effectively? What mechanisms will be put in place to ensure equitable participation and to manage potential conflicts that arise from differing goals and expectations? Addressing these questions is crucial to forming a truly collaborative and effective transdisciplinary research team (Hirsch Hadorn et al. 2008).

Summarising, for the first phase of an inter- and transdisciplinary research endeavour, it is essential (i) to carefully explore and delimit the problem to be studied and (partially) solved, (ii) to recognise and characterise the variety of actors that are engaged and/

or concerned with the problem and its solution, (iii) to acknowledge their interests, influence and agencies with respect to the issue and (iv) to build an operational, well-working team with effective communication and collaboration practices.

37.2.2 The Co-creation of Solution-Oriented Transferable Knowledge

The second phase of the transdisciplinary research focuses on the collaborative development of knowledge and solutions. This is where the core work of co-creation of knowledge and solutions takes place, building on the problem framing and team building efforts of the first phase. For both inter- and transdisciplinary research, co-creation integration can be considered the core methodology, essential for synthesizing diverse perspectives, generating and integrating several types of knowledge, and practicing methodologies to address the complexity of real-world problems (Pohl et al. 2008, 2021).

37.2.2.1 Mobilising Different Types of Knowledge

The diversity of knowledge and information is elaborated in a working process that highly depends on the nature of the problem, the research questions and objectives, the capacities and interests of the involved actors, the resources at hand, etc. As illustrated in Fig. 37.2, the process of knowledge co-creation is characterised by a dense fabric of interactions, and a huge diversity of outputs in both tangible and non-tangible forms. The distinction between three types of knowledge, namely *system, target and transformation knowledge*, is crucial for the effective organisation of the collaboration in the co-creation of knowledge, as they have different origins and functions (Hirsch Hadorn et al. 2008). *System knowledge* is about the understanding of an issue; *target knowledge* is required for determining the possibilities and boundaries of decision-making and provides orientation; and *transformation knowledge* informs about the ways and means of practically realizing such decisions (Becker 2002; Jahn et al. 2012).

Systems knowledge refers to an understanding of the nature of a problem, the causalities and conditioning context in terms of the current state and ability to change.

Target knowledge is defined as an understanding of actors' interests, concerns and capacities, and is developed on the basis of values and norms that guide decision-making. It considers the scope of action and problem-solving measures and focuses on desired states, potential risks and benefits under prevailing uncertainties.

Transformation knowledge is crucial in order to describe a path, the operational steps from the current to a desired state. It provides answers about changing practices and institutions and enables practitioners to achieve the competence to foster, implement and monitor progress and to adapt and change behavioural attitudes.

Excursus 37.3 Different Types of Knowledge

In the example of biofuels, knowledge about the biofuel production and processing would fall in the 'systems knowledge' category. Scientific knowledge is particularly important for the analysis of problems, while the definition of the problem may be derived from science but also from the societal context (lifeworld) itself. However, local actors may also hold and

contribute substantial practical knowledge about many aspects of the functioning of the investigated system, e.g., farmers have practical knowledge about how to produce best on their land and under the given natural and climatic restrictions. Then, the question whether and to what degree fossil energy or bio-based resources and materials shall be used in transportation is one that is solved based on target knowledge. Finally, transformative knowledge encompasses all options and decisions taken to make a shift from fossil to renewable energy happen.

37.2.2.2 Integrating Knowledge Across Disciplines and Professional Boundaries

Complementary to the creation of knowledge, its integration within the larger body of co-created knowledge is the second key component within this phase. Integration, in this context, is understood as an iterative and open-ended process, which involves the process of creating novel connections between previously unrelated elements within a research framework (Jahn et al. 2012; Pohl et al. 2021). Keestra (2017) elaborates on this by describing integration as a metacognitive process, where individuals reshape their mental constructs when exposed to different views, leading to new, emergent understandings that transcend the original components. This process does not necessarily aim for consensus; different perspectives can co-exist through continuous exchange and learning in what Boix Mansilla et al. (2016, 298) refer to as 'system of thought in reflective equilibrium'.

> ***Knowledge integration*** is the 'cognitive operation that establishes a novel, hitherto non-existent connection between distinct entities of a given context' (Jahn et al. 2012, p 3). Integration is an interactive and open process of constructing knowledge based on previously unrelated elements such as ideas or views of individual researchers and practitioners (Pohl et al. 2021, p. 23).

Basically, it is important to recognise that there is no standardised methodology for achieving knowledge integration (Pohl et al. 2021). The processes and strategies employed can vary significantly depending on the purpose, scope and scale of the research purpose, and the specific nature of the problems and questions being tackled (Klein 2008). Three forms of transdisciplinary collaboration for knowledge integration mentioned in the literature are (i) common group learning, (ii) deliberation among experts and (iii) integration by a subgroup or individual (Pohl and Hirsch Hadorn 2008). While in the first case cooperation happens as a whole group learning process, in the second case team members with relevant expertise on the components of the problem join their views in the form of a deliberative process. In the third case, the act of integration happens through the work of a specific sub-group or an individual who work(s) on the behalf of all (Pohl and Hirsch Hadorn 2008, p 115).

Excursus 37.4 Forms of Collaboration

Let's consider our earlier example on the bioeconomy project focused on assessing the conditions under which agriculture can provide raw materials for the construction sector. We illustrate how different forms of collaboration can be applied in this context

- Common group learning: All participants, including agronomists, farm economists, farmers, construction engineers and material processing experts, engage in regular joint meetings to discuss and learn together.

They collaboratively explore how agricultural practices and construction need to intersect, iteratively refining their understanding and approach.
- Deliberation among experts: Agronomists and construction engineers separately analyse how different crops could be used as construction materials. They then come together in focused sessions to negotiate the best approaches, sharing findings and adjusting their methods based on mutual feedback to ensure both agricultural and construction standards are met.
- Integration by a subgroup or individual: A project leader oversees the work of different expert groups. Agronomists, engineers and market analysts work within their specialised teams to gather data and insights. The leader then integrates these sub-results, ensuring that the final research output is coherent and aligns with the project's overall goals.

37.2.2.3 Implementing Collaboration in Inter- and Transdisciplinary Teams

Finally, the process of knowledge co-creation and integration also has a practical, interactional dimension, which is translated in a way that the communication among the involved actors is concretely organised (Jahn 2008). Actually, interaction in inter- and transdisciplinary research can be realised with an increasing degree of shared participation and responsibility. This scale is well represented by Pretty's (1995) 'ladder of participation', a model that categorises levels of actor engagement from passive involvement to active co-production. Although originally developed for development projects, this model is valuable in research contexts to describe how varying degrees of interaction among project partners and in working teams—from mere information-sharing to deep collaboration—can influence the co-creation of knowledge (◘ Table 37.1). While 'participation' may not fully encapsulate the complex roles scientific and non-academic actors play in research, this framework highlights the importance of strategically matching the level of interaction to the specific needs and goals of the research process.

Summarizing the second phase of an inter- and transdisciplinary research endeavour, it is crucial (i) to facilitate the integration of diverse types of knowledge, including systems, target,

37

◘ **Table 37.1** A typology of participation levels in research projects (modified following Pretty 1995, p 1252)

Type of participation	Characteristics of type
Manipulative participation	Actors' inclusion is a pretext; they have no functional role.
Passive participation	Actors are considered as 'learners', they receive information.
Participation by consultation	Actors contribute with information by answering questions of knowledge, perceptions and opinions. They have no part in decision-making on the project's issues.
Participation for material incentives	Actors contribute to research with information and/or labour etc. and receive in turn material advantages and resources
Functional participation	Actors are involved as their competences, resources and/or societal position are relevant to the aim of the project. They may have an influence in the research design and decision-making processes related to the project's implementation.
Interactive participation	Actors participate as equal partners throughout the research phases, participate in decision-making and share responsibilities and resources.

and transformative knowledge; (ii) to ensure that the formats and levels of interaction among actors are appropriately matched to the complexity and demands of the knowledge being integrated; and (iii) to maintain flexibility in the intensity of interactions, allowing them to adapt dynamically to the needs of the research process.

37.2.3 (Re-)integration and Application of Created Knowledge

Research outcomes of transdisciplinary research (concepts, methods and products) are evaluated from two different perspectives. Firstly, outcomes are assessed with regard to their usability, their practical relevance. Local actors care for their case and not for any general knowledge. To solve the problem 'in principle' would not be acceptable to the audience and the local actors who push the case. Thus, each case has its individual value, because the involved actors are engaged in solving their specific issue, not a general problem!

Secondly, scientists search for the more general features of a case and the advancement of scientific knowledge in general. The evaluative question here is: are the cases telling us that some nomothetic lessons can be learned despite their situational conditions, or that lessons can be learned because they are embedded in real world contexts?

In general, transdisciplinary research with high scientific impact remains challenging, mostly because of the reproducibility of the methods. Although there are formative evaluations (criteria to assess the principles of transdisciplinarity) and scientific outcome assessments (bibliometrics), it is more challenging to track the societal impacts of transdisciplinary research because such impacts occur with significant delays, the causal links are often difficult to establish and the complexity level of the problems and the solutions adopted is high (Lang et al. 2012).

Two major tensions influence the choices made during the implementation of a cocreation research project: (1) the relevance of impact vs. the relevance of the process and (2) the tension between having control of actors vs. inclusion of actors (Chambers et al. 2021). When dealing with those tensions, conflicts and trade-offs, project management, communication and leadership play a decisive role (OECD 2020).

Excursus 37.5 Frequent Challenges in Transdisciplinary Research

Lack of coherent framing: The use of transdisciplinary research in sustainability science is increasing, but under diverse terms, there is no common glossary, no focused communication platform and no commonly shared research. Overlaps with other concepts and terminologies (action research, citizen science, triple or quadruple or quintuple helix, interactive innovation, co-innovation and co-creation) can be a major obstacle to effective communication and collaboration between different communities (OECD 2020).

Integration of methods. The openness and diversity of methods have the advantage of adaptability to different contexts but affect the reproducibility of results and therefore the use for standardised frameworks (Brandt et al. 2013). On the other hand, the study of empirical cases shows that there are no clear relations between the theoretical concepts (phases and type of knowledge) and the methods. Practitioners' engagement: Although knowledge sharing and collaboration are happening, empowerment of stakeholders is still rare (Brandt et al. 2013). This could be caused by the design of the project or its conflict management implementation (Chambers et al. 2022), the lack of familiarity of the actors with engagement, or the vagueness and ambiguity of the expected results (Lang et al. 2012). Lang et al. (2012) mention the 'fear of failure' as an important factor limiting actors' participation, either because of the

offering of prepackaged (technical) solutions without involving practice partners or endless collaborative research continuously postponing the solutions (knowledge-first trap). New approaches, such as financing the development of the proposal or the notion of 'researching-by-doing' (such as learning-by-doing), can create space for reflection and iterative cycles (Lang et al. 2012).

Generating and measuring impact: Generating transdisciplinary research with high scientific impact remains challenging, mostly because of the reproducibility of the methods. Although there are formative evaluations (criteria to assess the principles of transdisciplinarity) and scientific outcome assessments (bibliometrics), it is more challenging to track the societal impacts of transdisciplinary research because such impacts occur with significant delays, the causal links are often difficult to establish and the complexity level of the problems and the solutions adopted (Lang et al. 2012).

37.3 Practices and Tools to Support Inter- and Transdisciplinary Research

With respect to the practical implementation of transdisciplinary research, the most important factors for success or failure are those related to the handling of the collaboration process, or specific management skills: e.g., the way the process is designed over time, the framing and operationalisation of the problem, the ability to select and appropriately involve participants, the systematic representation and consideration of various actors' interests throughout the work, professional facilitation of the potentially open process and the ability to balance power dynamics among participants (de Vente et al. 2016).

The success of transdisciplinary research is largely dependent on the capabilities of the project's leadership, who must navigate a multitude of academic disciplines and practice-related interests and concerns, particularly in situations where mandates and/or lines of authority are unclear. The structures formed during the project should be able to manage expectations and occasional loss of enthusiasm among partners who do not see particular elements as related to their personal or professional objectives (expectations about publications, language barriers and ownership of intellectual property).

As a guidance for project management and, complementary to the three phases of inter- and transdisciplinary research projects presented in ▶ Sect. 37.2 (problem framing, co-creation of new knowledge and assessment and re-integration of knowledge), we introduce the project management cycle with the four phases design, planning, implementation and synthesis and assessment phase (see ◘ Fig. 37.3). These parallel strands of process phases illustrate the two-layer management activities that are required for successful project implementation, namely the cooperation among heterogeneous actors and the achievement of (interim) results.

In the course of these research phases, different working steps must be carried out jointly by all or some of the team members. A range of formats and methods are available for this, and there is an impressive number of toolboxes, manuals, online repositories, platforms and other documentaries, which inform about frameworks, methods and tools to guide and conduct particularly transdisciplinary research in an inclusive manner. In the next section, we present a selection of those sources for information, with a focus on those that revealed particular insightfulness when used in teaching on inter- and transdisciplinary approaches in the bioeconomy. These examples are organised in line with the above-mentioned project management phases.

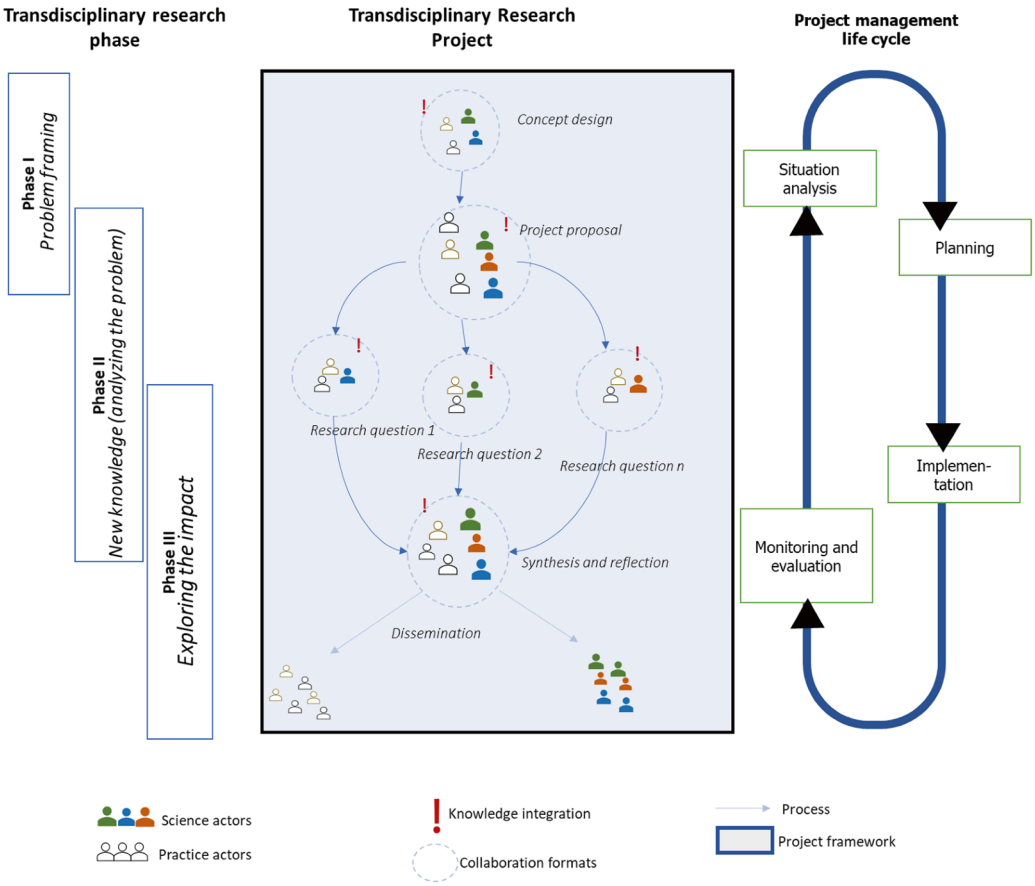


Fig. 37.3 Project life management stages in TDR projects. (Source: adapted from Pohl et al. (2021) and Hoffmann et al. (2017))

37.3.1 Tools Tailored for Transdisciplinary Research in the Bioeconomy

There is a vast range of tools and toolkits developed from social science, participatory research and business management that aim at making interactive, equitable collaboration happen. Each tool serves a specific purpose, employs a distinct procedure and is supported by a community of practice. The first and most important thing to consider when deciding on which tool to use is the expected result, the type and number of participants and the conditions of the context. An example on how the choice of tool is determined by the desired type of knowledge integration and the project's general purpose and expected impact pathway is presented in Fig. 37.4.

> A ***tool*** is in general very broad, and therefore, we use the term tool as an activity that has an expected purpose and outcome and can be applied in a determined period of time, involving several actors and using a predefined procedure. Some of those activities are small exercises of short duration, others are a sequence of steps to achieve a broader objective and others can be classified as a 'mindset' or a 'battery' of tools.

Effective deployment of any tool requires the active involvement of all relevant stakeholders. An effective knowledge integration strategy must consider the emotional and social–interactional dimensions, in addition to the cognitive dimension (Pohl et al. 2021). It is, therefore,

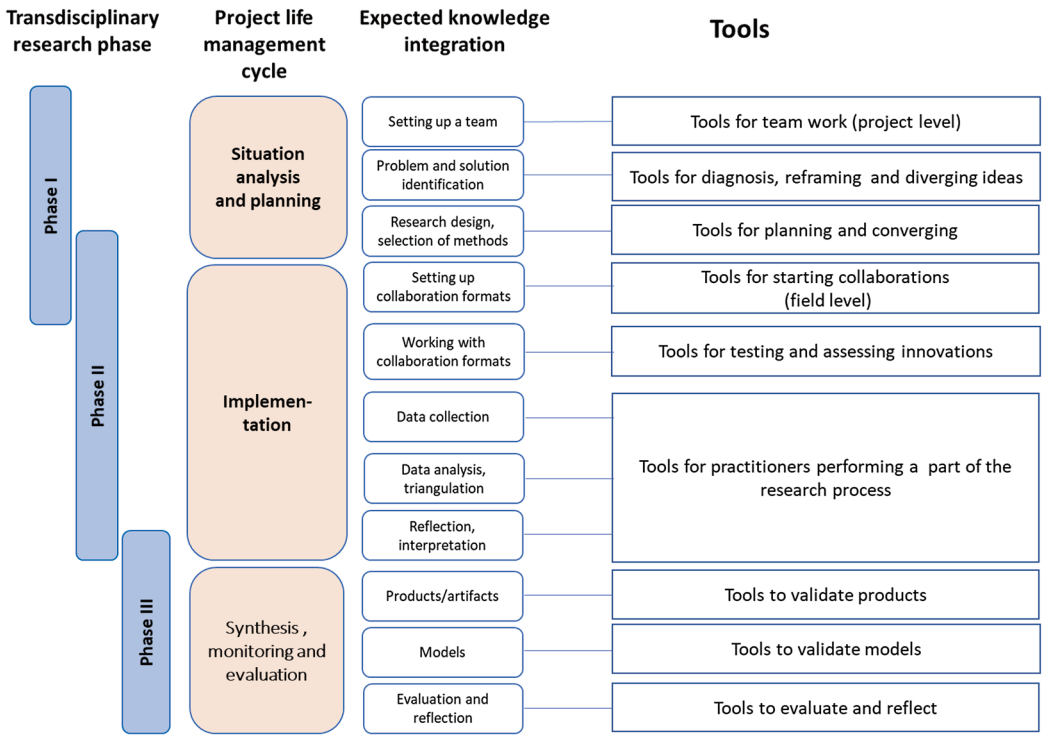


Fig. 37.4 Overview of the tools according to the phase, the management cycle and the desired integration of knowledge (Herrera et al. 2023)

critical to have the necessary facilitation skills in place to ensure the successful implementation of the tools. Furthermore, it is equally important to address the ethical considerations that arise from the application of integration methods, given the inherent power imbalance and the need to manage the different expectations across the project life cycle (OECD 2020).

To demonstrate how effective collaboration for inter- and transdisciplinary research can be realised in a stepwise manner using tools, we present in the following sections a number of examples that have been adapted for and tested with bioeconomy students in various rounds and on targeted examples. Each tool is briefly described, and links to further background information are provided.

37.3.2 Tools for Analysing Systems and Problems

During the first phase of collaboration between different stakeholders, it is usually the case that the problem needs to be framed according to the disciplines, experiences, objectives and resources of the participants involved. In those situations, tools to be applied have the purpose of building a consensus in a group of people about problems, challenges, boundaries and key stakeholders. The scope of the tools to be selected differs on the type of problems. We identified two potential tools to be used in this first phase.

The first one is an analysis of the system, using causal loop analysis. The objective is to describe the systems and all the variables that are affecting a specific problem. The tool allows one to make evident and ponder the elements in a structured way without predefined ideas that can limit creativity. System Mapping Academy (2023) suggests a three-step procedure: problem framing, exploring the variables affecting the problem framed and mapping the diagram. As a final output, the group reaches a consensus on how to visually represent the variables aggregated into

system components and how different causal loops influence the interactions within the system. Depending on the complexity of the issue at hand and the quality of the analysis, the result is transformed into a concerted diagnosis of a situation that is to be addressed collectively.

Another commonly used approach during the problem framing or design of a project is what is called a Theory of Change. This is based on the structural analysis of the problem, determining elements in a linear structure and making cause and effects explicit with the objective of deciding if and how to tackle the problem. There are as many variations of Theories of Change. Usually, the theory of change consists four steps: first, a 'problem tree' is agreed upon with the participants, identifying the problem and the most relevant causes. During a second step, the group agrees on the strategy to address feasible objectives to solve the root causes of the problem. During a third step, a clear relation between inputs, outputs, outcomes and impacts is revised and refined. After that, the Theory of Change is visualised. During the last step, indicators of performance of those levels are agreed within the group. The advantage of building a Theory of Change is that the analysis of the problem could be intuitively transformed into actionable solutions, indicators and articulated as a programme and roadmap of actions. The development and use of a Theory of Change offers a structured way to plan for impact in transdisciplinary research by making the underlying causal logic of an intervention explicit and testable.

Excursus 37.6 Tools for Analysing Systems and Problems: Causal Loops Analysis and Theory of Change

While analysing a complex problem such as food waste, a group of students used the tools for system analysis and the linear cause–effect analysis. The outcomes of the analysis can be seen below. The first graph exemplifies the variables and loops between variables as perceived by the group members; multiple aspects were identified and grouped into three big topics: consumption patterns, production and distribution. The broad picture depicts elements in those three aspects that contribute to food waste. The second graph shows the problem tree for food waste as a result of the problem tree and objective tree analysis. Both types of analyses can be done in the same project as they do not substitute each other but are rather complementary: the system analysis offers a broader and probably unstructured perspective, while the theory of change organises the problem in terms of solutions that can be implemented in a feasible and logical way. In other words, the system analysis is based on system knowledge, while the theory of change generates target knowledge (Figs. 37.5 and 37.6).

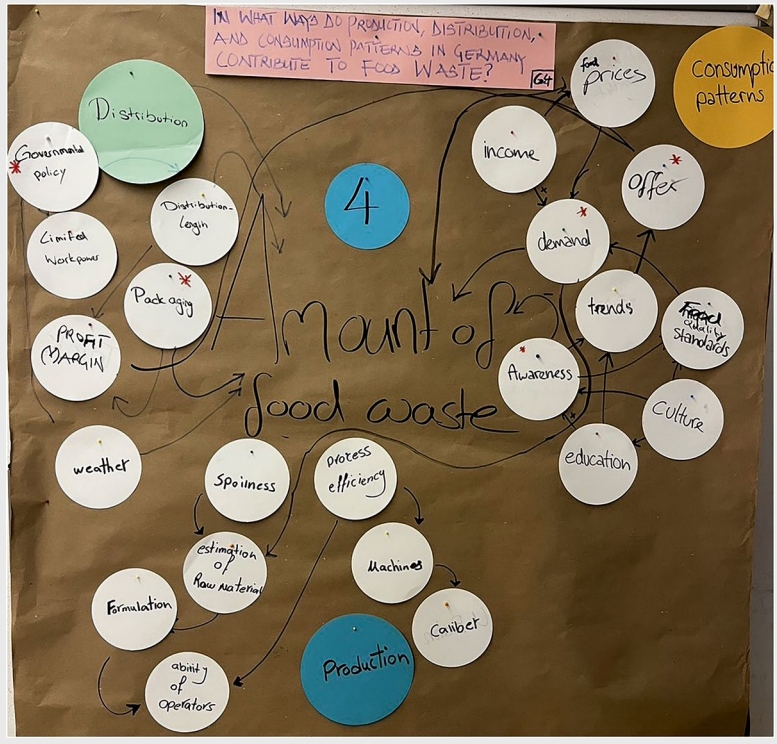


Fig. 37.5 Graph exemplifying the variables and loops between variables as perceived by the group members

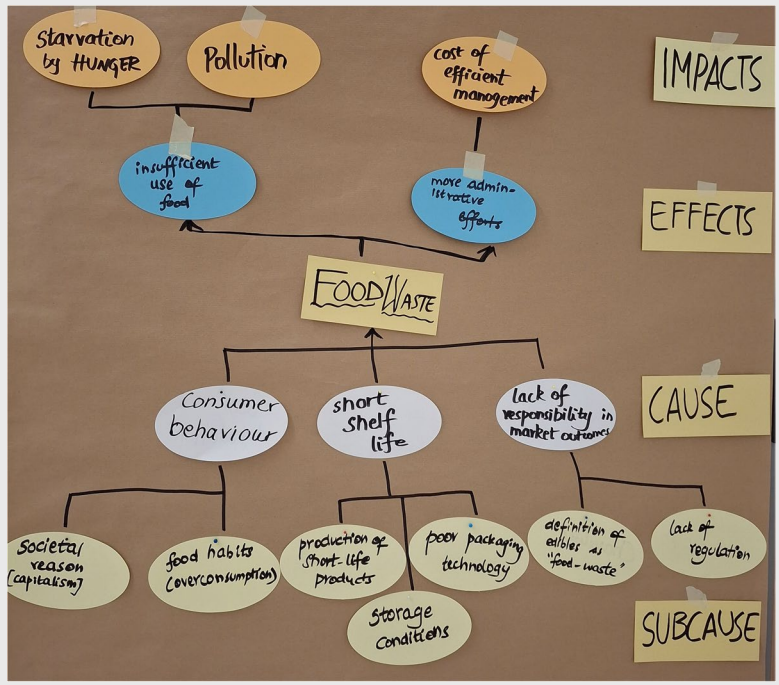


Fig. 37.6 Graph representing the problem tree for waste as a result of the problem tree and objective tree analysis

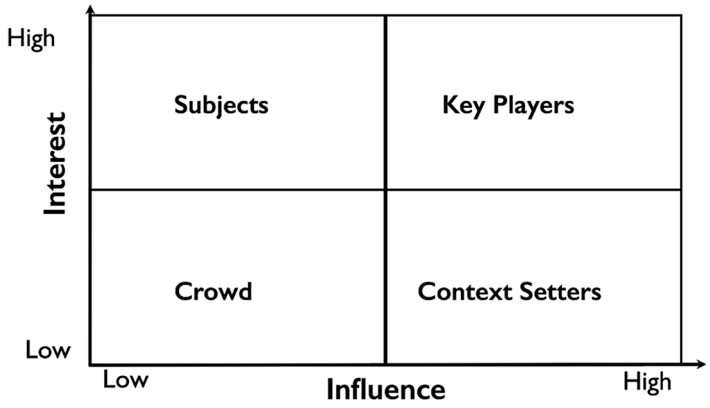


Fig. 37.7 Matrix for classifying stakeholders according to interest and influence (Grimble and Wellard 1997, p 176)

37.3.3 Tools for Identifying and Classifying Stakeholders

In order to appropriately address practitioners and to understand and assess roles, agencies and power constellations of actors involved, a stakeholder analysis is an essential step (Gerster-Bentaya 2015). In the case of a top-down "analytical categorizations" stakeholders are characterised by researchers or experts, while bottom-up "reconstructive methods" allow the categorizations and parameters in a stakeholder analysis to be defined by the stakeholders themselves.

General stakeholder classification criteria may be based on interest and influence, legitimacy, resources and networks or types of activities. The Influence-Interest II- Matrix (Fig. 37.7) is commonly used to categorise stakeholders according to their interest and influence.

Although the II-Matrix is very intuitive, many analyses fail to identify important stakeholders due to an insufficient clarification of 'interests' and sources of 'influence'. The level of interest is mainly about achieving benefits, but it is also about avoiding burdens. In the constructed case of agricultural raw materials for the construction sector, competing producers, e.g., from forestry, would be considered as stakeholders too. Benefit and burden sharing is central to any type of project. However, benefits and burdens may be direct and immediate or indirect and long-term. Also, not all impacts are material. Cultural impacts are usually symbolic and immaterial (e.g., social recognition). Also, interest does not necessarily imply active involvement. Sometimes actors are not aware of possible costs and benefits or incapable of acting and thus appear to be 'passive' (Nagel 2001). Actors may be able to influence the outcome of a project even if they do not have an interest in the project's outcome.

Excursus 37.6 Identifying Stakeholders of a Reducing Food Waste Project

In a project about food waste, the group of students identified consumers in the middle, with government, supermarkets and producers as context setters. Also, media, local government and organizations were identified as key players in this particular case, where the project has a strong component in creating awareness of the problem among consumers and farmers. Local NGO, funders and community groups are the subject of the intervention. Other actors such as landowners or employees were considered as not directly involved but only informed. By definition, complex problems can be solved with different interventions, each depending on the discipline present in the key team. This means that the characterisation of stakeholders can be very different according to the focus and scope of each intervention (Fig. 37.8).

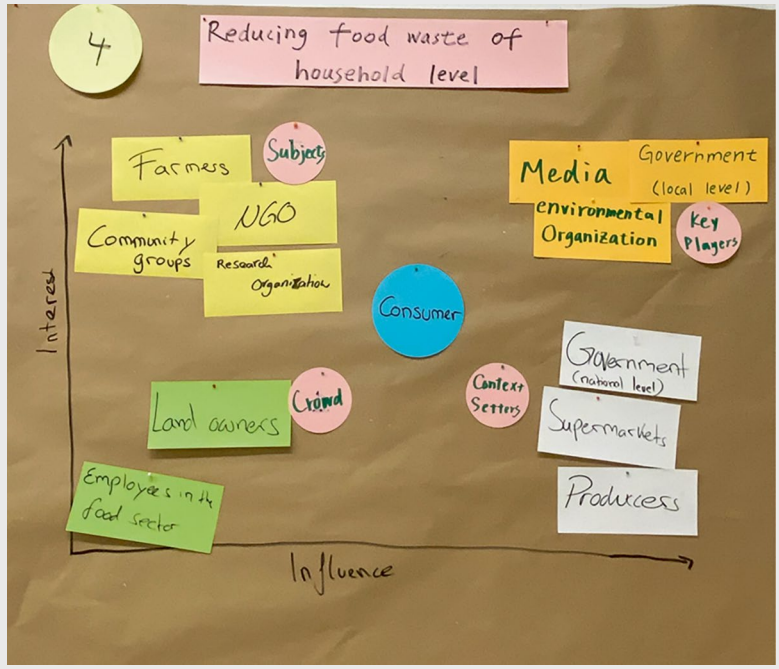


Fig. 37.8 Identified stakeholders of a reducing food waste project

37.3.4 Tools for Navigating Knowledge Integration Along the Execution of the Project

During the life cycle of a project, there are different points where knowledge is integrated. The methodological approach used to involve actors in the joint research and development process of a transdisciplinary study is crucial for the participation achieved. As a way to approach knowledge integration, Pohl and Hirsch Hadorn (2008) propose as 'means of integration' four 'classes of tools': mutual understanding, theoretical concepts, models and products (ibid). Obviously, the question of mutual understanding is one of having a common language, of seeking to avoid too specific, disciplinary terms and of spending time on explanation and listening. Secondly, 'challenges in integration are about creating or restructuring the meaning of theoretical and conceptual terms to capture what is regarded as relevant in problem identification and framing. Therefore, a second group of integration 'tools' comprises theoretical notions [theoretical concepts], which can be developed by (1) transferring concepts between fields, (2) mutually adapting disciplinary concepts and their operationalisation to relate them to each other, or (3) creating new joint bridge concepts that merge disciplinary perspectives' (ibid, p 116). As third means of integration, Pohl and Hirsch Hadorn (2008) propose models—ranging on a continuum from purely quantitative (mathematical) to purely qualitative (descriptive) and they emphasise that '(semi-)qualitative system dynamics models are often developed in a collaborative learning process among researchers and other stakeholders, aiming at a shared understanding of the system, its elements and their interactions'. Finally, as a fourth means, products are designed, which can be of any kind, such as marketable products, knowledge-sharing devices or even institutions.

Excursus 37.8 Means of Integration or Classes of Tools

Following the earlier example on the bioeconomy project focused on assessing the conditions under which agriculture can provide raw materials for the construction sector, we can identify potential tools or means of integration.

- **Mutual understanding**: the project is organised in teams according to the components or expected outputs (Working Groups). Teams of different disciplines meet and exchange on the progress of the project at least once per month with regular annual project meetings.
- **Theoretical concepts**: Each Work Package develops its own research questions or hypotheses to test. According to the disciplines, the development of the research questions includes the involvement of practitioners. Theoretical frameworks are based on the interaction of different actors.
- **Models**: During the research process and as part of the analysis, some of the working groups develop theoretical models that can serve as research process (analytical models) or practice (decision support models).
- **Products**: Along the project timeline, products (construction materials based on biological sources) are designed, prototyped and tested within the Working Groups and the partners, identifying the features that allow for a feasible production and a promising scaling of the new products. Start-ups or other forms of exploitation of products are incentivised.

37.3.5 Tools to Create Awareness for the Process and its Outcomes

Transdisciplinary research projects require constant assessment and reflection on the process and outcomes. The level of assessment varies according to the degree of control and the expected outcome.

This constant assessment and awareness creation of the outcomes is done through what is called monitoring and evaluation (M&E). *Monitoring* can be understood as the continuous and systematic collection of data on specified indicators to assess an intervention (project, programme or policy), its implementation in relation to activity schedules and expenditure of allocated funds, and its progress and achievements in relation to its objectives. Monitoring is usually done by internal staff, and as a main purpose, it allows the managers to make changes to the operational planning and to involve internal staff in the reflection of daily activities.

In contrast, *evaluation* is the assessment at one point of time, of the design, implementation, outcomes and impact of an intervention. It assesses the relevance and achievement of objectives, and the performance of the implementation in terms of effectiveness and efficiency, and the nature, distribution and sustainability of impacts. The purpose of the evaluation is to assess the strategy and determine whether changes in policies, strategies and future work are necessary. Very frequently evaluation is used for making decisions by project managers and also by external stakeholders such as funders, beneficiaries or other stakeholders. For that reason, they are usually conducted by persons external to the project.

In transdisciplinary research projects, monitoring and evaluation could also be done involving practitioners. The monitoring and evaluation actively engaging stakeholders is called Participatory Monitoring and Evaluation (PM&E). PM&E is a process through which stakeholders at various levels engage in monitoring or evaluating a particular project, program or policy and share control over the content, the process and the results of the monitoring and evaluation activity, and also engage in taking or identifying corrective actions. PM&E processes can contribute to results-based management by improving policymaking, facilitating adaptive management, enhancing efficiency and promoting staff motivation. Additionally, PM&E improves the exercise of power because it facilitates sharing information and dialogue

between partners, which contributes to openness and transparency to develop long-term partnerships. The difference between conventional M&E and PM&E is given by how stakeholders participate along the process of design and implementation of the monitoring and evaluation process (Table 37.2).

One central component of the monitoring and evaluation activities is what is going to be measured. The piece of information that indicates the progress in one area is called *indicator*. Indicators allow to objectively verify the attainment of an intended output. They are defined and formulated parallel to the objectives, and serve as a parameter for comparing the targeted with the actual output later on (monitoring).

> An ***Indicator*** is a quantitative or qualitative factor or variable that provides a simple and reliable means to measure achievement, to reflect the changes connected to an intervention or to help assess the performance of a development actor (DAC-OECD 2002).

In conventional M&E, indicators are selected according to the preestablished objectives of the project. In PM&E, stakeholders get involved in determining which information indicates the success of the project. In general, good indicators present the following characteristics:

- *Relevant*. Good indicators represent most of the important aspects of implementation and of the outcomes and impacts intended.
- *Clear*. Indicators must be unambiguous and clearly defined in the project's context, and in a manner understood and agreed upon by all stakeholders.
- *Specific*. Indicators should measure specific changes, and be specific to a timeframe, location and target or another stakeholder group.
- *Measurable*. There have to be practical ways to measure the indicator, either in quantitative or qualitative terms, that are within the capability of the monitoring organisation.

Table 37.2 Differences between conventional M&E and participatory M&E

Conventional M&E	Participatory M&E
Who is responsible for monitoring and evaluation activities? External (evaluation) or internal (monitoring) experts	Stakeholders, including community and project staff; external facilitators.
What is monitored and evaluated? Predetermined indicators to measure inputs, outputs, outcomes, impacts or sustainability	Indicators identified by stakeholders to measure progress, as well as outputs, outcomes or impacts
How the monitoring and evaluation activities are conducted? Focus on 'scientific objectivity'; distancing of evaluators from other participants; uniform complex procedures; limited access to results	Self-evaluation, simple methods adapted to local culture; open, immediate sharing of results through local involvement in evaluation processes
When the monitoring and evaluation activities are conducted? Usually upon predetermined periods of time completion; sometimes also mid-term	Merging of monitoring and evaluation, hence frequent small-scale evaluations
What is the main purpose of conducting the monitoring and evaluation activities? Project managers' decision-making and accountability, usually summative, to determine changes in strategies	To empower local people to initiate, control and take corrective actions

- *Consistent*. The values of the indicators should be reliable and comparable over time when collected using the same methods.
- *Sensitive*. Indicators should be sensitive to the expected changes. It is especially important that indicators are capable of revealing short-term improvements.
- *Attributable*. Based on an established or probable relationship expected to cause the intended change. In moving from inputs and outputs to outcomes and impacts, attribution must typically rely less on direct observation of cause and effect and more on statistical evidence of change and its probable cause.

Excursus 37.9 Participatory Monitoring and Evaluation in a Bioeconomy Project

In the example of the bioeconomy project aiming to reduce the food waste at household level, students conducted one exercise to identify potential indicators of the different levels of objectives. The indicators were identified by asking *what can indicate that we achieve the objective in question?* The agreement on the selection of indicators is challenging because different people make different judgements about what is important or relevant. In addition, the existence of scientific references on the subject can help (or complicate) according to the level of scientific consensus on a specific consensus. The graph below shows the final agreement of the group. Selecting and agreeing on a manageable set of indicators in a project dealing with complex issues is a challenging process. Project managers must balance between providing comprehensive information to showcase the full range of potential outcomes while avoiding unnecessary burdens that an excess of information might bring (Fig. 37.9).

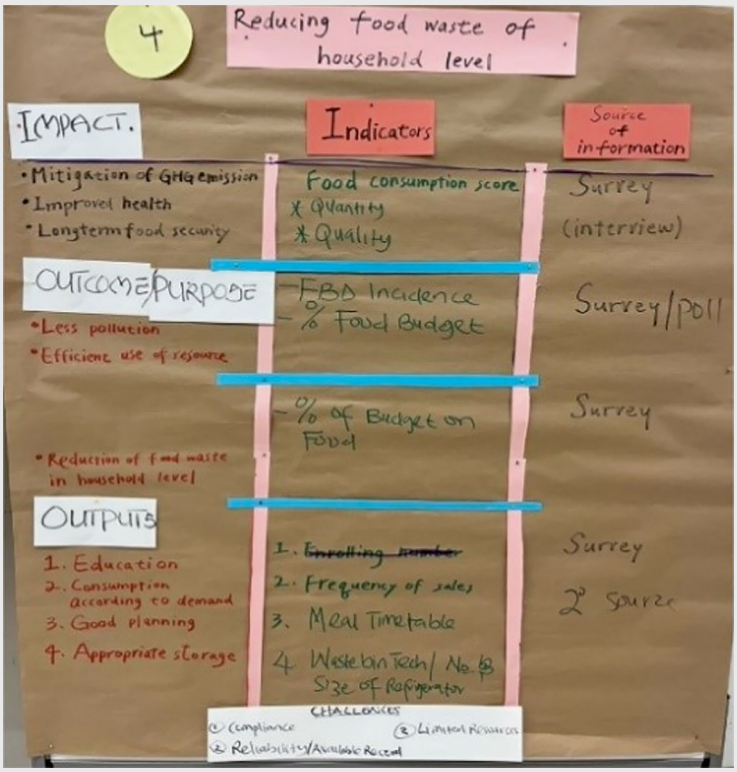


Fig. 37.9 Identified potential indicators of the different levels of objectives for the food waste project

37.3.6 Toolkits for Transdisciplinary Research

In this section, we have seen that the practice of transdisciplinary research projects requires a flexible and creative approach, with a variety of methods needed to address specific challenges. There are currently many institutions working in compiling and disseminating lessons learned based on the many decades of practice in the field. We recommend the readers interested in the application of transdisciplinarity to engage with the multiple resources available. Examples of sets of tools or toolkits have been developed to meet the specific needs of researchers, as illustrated in the following excursus.

Excursus 37.10 Example of Toolkits for Applying Transdisciplinary Research Principles

► TD-Net Toolbox

This web portal from TD-Net: Network for Transdisciplinary Research in the Swiss Academies of Arts and Sciences offers several tools and methods for collaboration between experts and stakeholders from science and practice to tackle real-word, context-sensitive societal challenges. The tools are structured by: key issues, phases of the transdisciplinary research process and also by method profiles.

► Transdisciplinary Field Guide—Practical toolkit Utrecht University-Field Guide

This web portal from the University of Utrecht has also gathered several useful tools and approaches for transdisciplinary research. The tools are structured by the three different phases: Starting well, Working together: processes and activities and, Sharing results and exploring impact.

► GAIA Journal—Toolkits for Transdisciplinarity series and participatory research methods for sustainability (GAIA 2007)

The Toolkits for Transdisciplinarity compile existing methods available for transdisciplinary researchers developed in different contexts and for different forms of collaborations. GAIA editions also include a toolkit series providing a synthesis of participatory research methods in sustainability science and showcasing exemplary case studies.

37.4 Researchers' Roles and Agencies

Due to the way inter- and transdisciplinary research is induced—frequently through third-party-funded programmes and project calls—researchers' roles in its initiation and design are often dominant. This constellation is the reason why we dedicate this last section to the roles, agencies and responsibilities that researchers have in inter- and transdisciplinary research.

The conceptualisation of the research starts with researchers' general understanding of what 'bioeconomy' is and how the studied problem is framed and relates to the bioeconomy. It continues with the judgement of which bioeconomy questions and challenges research resources should be allocated to, and it becomes more concrete in the conceptual framework that orients inter- or transdisciplinary research (Knierim et al. 2021). Throughout these steps, the researcher(s) strongly and more or less explicitly shape the way and propose rules, how bioeconomy research is understood and realised. Thus, researchers are important actors in the process of the 'institutionalisation of bioeconomy'.

Institutions can be defined in various ways. In abstract words, they are 'prescriptions that humans use to organise all forms of repetitive and structured interactions' (Ostrom 2005, p 3). The process of creating institutions (institutionalisation) in modern societies is often interpreted as a process of establishing and assigning new rationality criteria to specialised action arenas. In a sociological perspective, the transition to a bio-based economy

requires the institutionalisation of e.g., recycling or a preference of biomass usage over fossil resources, etc.

In most cases, the role of individual researchers with respect to the institutionalisation of the bioeconomy is by far not as influential as the one s/he has on the degree of interactive participation in the cooperation process. Here, it is the multitude of choices and decisions taken by one or a certain number of researchers engaged with the research that results in a more or less equitable participation of research partners in the decisions about objectives, channelling of funds, research questions tackled and research practices implemented.

Excursus 37.11 Institutions

A more general definition sees institutions as a set of stabilised social practices/interactions. This may be an individual morning ritual (breakfast with coffee, brushing your teeth, an institutionalised social group activity or interaction (e.g., having a joint family breakfast at 7 a.m.), collective structure (the family as a social institution) or even a wider organised social structure (e.g., the educational system). In a narrow sense, institutions are often defined as the 'rules of the game', thus referring to the normative order of individual practices and social interactions. From this perspective, institutions reduce the social complexity and ease individual choices (routine) but also social interactions, since actors do not have to negotiate all aspects of action situations. The establishment of a normative order requires a process of socialisation, in which actors learn (internalisation) and approve or modify a certain selection of norms and rules. Thus, institutions are related to (new) knowledge in the way that they require actors' knowledge to function but also offer values, meaning and knowledge to actors about 'why' and 'how to act'. Institutions also require external control and sanctioning (rewards as well as punishment) mechanisms (governance).

Summarising, researchers' impact on processes, outputs and outcomes of inter- and transdisciplinary research should not be underestimated. On the contrary, it is important to take the various roles, functions and tasks, which arise in the process of collaborative research, as serious as possible, and to accept and perform or reject (and if necessary, delegate) them openly (Knierim et al. 2013) in order to come to meaningful and reliable results that are relevant and appropriate to solving practical problems within society.

Furthermore, the introduction of systematic reflection as a means to enhance transparency of and professional distance in interactive engagement has proven to be effective (sources). Ison (2012:147) stresses that (i) reflection about such steps in the making of research, and (ii) reflexivity about 'why we do what we do' are essential to link the researcher's perspective with the 'situation outside of our selves'. Reflexivity is a system practice because it explores and reveals manifold linkages and interdependencies that individuals perceive among their deeds and various effects in their environment. Sharing such observations and insights with other actors in collaborative research creates the basis for overcoming information asymmetries, misunderstandings and power and status imbalances.

Do you want to learn more about interdisciplinary approaches in the bioeconomy context? Take a look at Supplementary Video 37.1, a video from our MOOC 'Concepts of Sustainable Bioeconomy' (2021).

Do you want to learn more about transdisciplinary approaches in the bioeconomy? Take a look at Supplementary Video 37.2, a video from our MOOC 'Concepts of Sustainable Bioeconomy' (2021).

Questions

1. What are similarities and differences between inter- and transdisciplinary research?
2. What are the phases of transdisciplinary research?
3. How do stakeholders engage in the different phases of transdisciplinary research?
4. What are challenges in designing, planning, conducting and assessing transdisciplinary research?
5. How do we select tools to be used in inter- and transdisciplinary research?
6. What are researchers' roles and agencies in inter- and transdisciplinary research?

Answers

1. Interdisciplinarity involves different disciplinary approaches to research in a conceptually coordinated way where the disciplinarily guiding assumptions and research concepts ('worldviews') are made explicit and mutually connected. In contrast, 'transdisciplinarity is a reflexive, integrative, method-driven scientific principle aiming at the solution or transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge'. Both approaches share core components like joint conception of the research problem and the integration of diverse knowledge.
2. The phases of transdisciplinary research are: Problem framing and team building phase, the co-creation of solution-oriented transferable knowledge phase, and (Re-)integration and application of created knowledge phase: Research outcomes.
3. In the problem framing and team building phase, 'actors are identified and understood according to their interest and influence', and their involvement helps shape the research scope and objectives through iterative discussions. In the co-creation of knowledge phase, stakeholders contribute to 'the diversity of knowledge and information' and participate in integrating system, target and transformation knowledge. In the (re-)integration and application phase, stakeholders focus on 'assessing the practical usability and relevance of research outcomes' to ensure solutions address their specific issues.
4. Challenges include a lack of coherent framing, difficulty in integrating diverse knowledge types and balancing power dynamics among participants. Additionally, generating transdisciplinary research with high scientific impact remains challenging mostly because of the reproducibility of the methods. The complexity of tracking societal impacts due to delayed outcomes is another key issue.
5. The first and most important thing to consider when deciding on which tool to use is the expected result, the type and number of participants and the conditions of the context. Tools must align with phases of the transdisciplinary research process and support methods such as system mapping or Theory of Change. Flexibility and the facilitation of knowledge integration are emphasised.
6. Researchers' roles include the conceptualisation of the research, the design and the implementation of the collaboration with other actors. They influence how bioeconomy research is understood and realised and make decisions about objectives, resource allocation and research practices. Reflexivity is essential, as it explores and reveals manifold linkages and interdependencies, ensuring transparency, equity and meaningful results in collaborative processes.

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The Bioeconomist

Lina Mayorga-Duarte, Jan Lask, Ricardo Vargas-Carpintero, and Jan Weik



Fig. 38.0 The Bioeconomist. (© Universität Hohenheim, Max Kovalenko) (► https://doi.org/10.1007/000-hvk)

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The transition towards a bioeconomy in a challenging and complex environment requires substantial interaction and collaboration between different players at multiple levels. This chapter discusses the concept of a bioeconomy professional who acts as a catalyst and change agent in this transition. This actor plays an integrative and connecting role for which the development of fundamental and key competencies is required. The concept of T-shaped profiles, built up from disciplinary expertise and the ability to integrate different disciplines and players holistically, is considered a defining feature of bioeconomists. To acquire such profile, interdisciplinary approaches and dedicated learning environments are required during education processes. Bioeconomists have relevant roles in all different stages of the value chain as well as in their initial establishment. Concluding this chapter, four perspectives of bioeconomy graduates are presented to provide an overview of the potential career opportunities available to these professionals.

Learning Objectives

After studying this chapter, you will…

- …be able to understand the role of the bioeconomist (see ► Sect. 38.1)
- …recognize the skills and competencies of a bioeconomist as well as their role as a collaboration catalyst (see ► Sect. 38.2)
- …realize the approaches and challenges of the bioeconomy education (see ► Sects. 38.3 and 38.4)

38

38.1 The Relevance of Bioeconomists in a Sustainable Economy

As discussed in previous chapters of this book, the transition towards a sustainable bioeconomy is viewed as a potential pathway to addressing significant global challenges such as climate change, the biodiversity crisis and socio-economic imbalances.

Addressing such sustainability issues requires ambitious and whole-scale transformations bridging science, policy, industry sectors and citizens. Due to the inherent complexity of such shifts, they are referred to as "wicked problems" (see ► Sect. 37.1.1). Wicked problems differ from "tame problems" in that they cannot be addressed using the linear logic of conventional rationality or understood solely through quantitative and objective information (Innes and Booher 2016). Approaching wicked problems requires a different strategy and logic than those usually applied to tame problems. Innes and Booher (2016) argue that a different kind of rationality, a so-called collaborative rationality "built on collaborative dialogue and multifaceted information", is needed to deal with wicked problems. This requires the integration of various views and perspectives under a "systems approach". Pacanowsky (1995) explains that whereas tame problems can be solved by thinking "inside the box", wicked problems force the solvers to think "outside the box".

A collaborative dialogue that engages the values, knowledge and perspectives of diverse stakeholders is essential for reframing wicked problems, rethinking and defining realistic goals and identifying possible solutions, thereby fostering the emergence of innovation (Innes and Booher 2016; Head and Xiang 2016). For this reason, transitioning towards a bioeconomy should be understood as a cross-cutting, iterative and adaptive endeavour that promotes both technological and social progress and innovation.

In line with the concept of a "collaborative dialogue", Innes and Booher (2016) highlight the need for planners who are skilled in setting up, supporting and conducting participative processes. In the context of sustainability transitions, these planners are often referred to as change agents, who promote sustainable development by initiating, managing or implementing change (Caldwell 2003). It is important to note that change agents can take diverse forms, as "change agency cannot be captured in one single model with a particular set of attributes or competencies" (van Poeck et al. 2017). ► Excursus 38.1 provides an overview of four prototypic change agents, each with different roles and approaches towards sustainability transitions.

Excursus 38.1 Typology of Change Agents (Based on Van Poeck et al. 2017)

Technician: Fosters change by providing expertise, insights and facts. Explains theoretical models, concepts and insights to inspire or encourage change.

Convincer: Emphasizes the need for radical societal change, often acting as an exemplar and serving as inspirational leader.

Mediator: Initiates change processes by establishing initiatives that mobilize new perspectives and actors, facilitating co-thinking and co-creating rather than doing the actual change work themselves.

Concerned Explorer: Raises awareness and calls attention to (sustainability) issues. Additionally, envisions change and proposes future visions.

Roles of change agents are never fixed but can take various forms. Additionally, they must always be considered within their specific context. Against this backdrop, this chapter introduces and describes a special type of professional: the bioeconomist, who acts as a change agent for the transition from a fossil-based economy to a bioeconomy—a systemic shift that involves multiple complex challenges, goals and agents.

38.2 Bioeconomists' Roles, Competencies and Profiles

Due to the diversity and vast scope of the bioeconomy, bioeconomists may become active in a wide range of sectors and positions, working within academia, (non-) governmental organizations and industry. Irrespective of their position, their role is crucial for the transition towards a sustainable bioeconomy. Bioeconomists are active facilitators who follow a collaborative rational approach to solving wicked problems. They are catalysers of change and therefore, enable interaction among stakeholders and create participatory solutions to specific challenges, with the ultimate goal of implementing innovative solutions.

The success of these collaborative endeavours largely depends on the capabilities of the facilitators, who must navigate a multitude of academic disciplines and practice-related interests. These facilitators must manage expectations and occasional loss of enthusiasm among participants and stakeholders, acting not only as moderators but also as supporters of the practical implementation of innovations towards a bioeconomy.

Despite the potential variety of roles that bioeconomists can take on, certain challenges typically arise due to the inter- and transdisciplinary nature of the bioeconomy:

- How can different values and priorities be navigated within the intricate interconnections between ecological, social and economic systems?
- How can the expertise and knowledge of diverse actors be effectively integrated?
- How can equitable participation be ensured while managing potential conflicts?
- How can a good communication between different disciplines be achieved?
- How can inclusive participation be ensured in innovative projects?

To address these challenges, bioeconomists require a professional profile comprising a set of dedicated core skills and competencies. In the following definitions, the concept of competencies and skills is shown. These are used for conceptualising abilities and providing an explicit, commonly shared framework that supports the description of professional profiles (Wiek et al. 2011).

The Organisation for Economic Co-operation and Development (OECD) defines ***competencies*** as the "ability to meet complex demands by drawing on and mobilising psychosocial resources (including skills and attitudes) in a particular context" (Ananiadou and Claro 2009, p.8). For instance, the ability to collaborate effectively in an interdisciplinary team is a competence that depends on an individual's capacity to understand different scientific languages (knowledge) and their attitude towards other team members.

Skills are defined as "the ability to use one's knowledge with relative ease to perform relatively simple tasks" (Rychen and Salganik 2000, p.8), while ***knowledge*** is described as the "facts or ideas acquired by study, investigation, observation or experience and refers to a body of information that is understood" (Rychen and Salganik 2000, p.8).

A simple set of basic and key competencies is required for most professional profiles. Both types of competencies are equally important; however, the latter are specific to a particular scientific field or profession and emphasize specialized abilities. While these are clearly necessary competencies for supporting the change towards a sustainable bioeconomy, they are not sufficient, as they are not distinct from the requirements of the bioeconomy.

As sustainability is a core principle of the bioeconomy (see ▶ Chap. 3), sustainability-related skills and competencies are also crucial in the bioeconomy context. For this reason, an established framework of sustainability competencies should form the foundation for all profiles of bioeconomy professionals. Building on previous work (Wiek et al. 2011), Redman and Wiek (2021) identify eight key sustainability competencies. These include five established competencies—systems-thinking competence, anticipatory competence, normative competence, strategic competence and interpersonal competence—and three emerging ones: intrapersonal competence, integration competence and implementation competence (see ▶ Excursus 38.2 for further explanation).

Excursus 38.2 Key Competencies for Sustainability (Redman and Wiek 2021, p. 6)

Systems-thinking competence: "Ability to appl modelling and complex analytical approaches (1) to analyse complex systems and sustain ability problems across different domain (environmental, social and economic) an across different scales (local to global), includ ing cascading effects, inertia, feedback loop and other system dynamics; (2) to analyse th impacts of sustainability action plans (strate gies) and interventions (evaluating how the change systems and problems)"

Futures-Thinking Competence: "Ability t carry out or construct simulations, forecasts scenarios, and visions: (1) to anticipate futur states and dynamics of complex systems an sustainability problems; (2) to anticipate hov sustainability action plans (strategies) migh play out in the future (if implemented)."

Values-Thinking Competence: "Abilit to identify, map, specify, negotiate and appl sustainability values, principles and goals: (1 to assess the sustainability of current and/o future states of complex systems; (2) to con struct sustainability visions for these system and (3) to assess the sustainability of actio plans (strategies) and interventions".

Strategies-Thinking Competence: "Ability to construct and test viable strategies (action plans) for interventions, transitions, and transformations toward sustain-ability".

Implementation Competence: "Ability to put sustainability strategies (action plans) into action, including implementation, adaptation, transfer, and scaling, in effective and efficient ways".

Inter-personal Competence: "Ability (1) to collaborate successfully in inter-disciplinary and -professional teams; and (2) to involve diverse stakeholders, in meaningful and effective ways to advance sustainability transformations".

Intra-personal Competence: "Ability to avoid personal health challenges and burnout in advancing sustainability transformations through resilience-oriented self-care (awareness and self-regulation)".

*Integration Competence: "*Ability to apply collective problem-solving procedures to complex sustainability problems: (1) to develop viable sustainability strategies (action plans); and (2) successfully implement them, in collaborative and self-caring ways".

The described sustainability competencies are context-independent and need to be complemented by other competencies, specifically context-specific disciplinary competencies (Dale and Newman 2005; Demssie et al. 2019). This means that bioeconomists need to possess knowledge of bioeconomy-related skills. They are expected to be specialized in one field but also able to understand the scientific language of associated disciplines relevant to the bioeconomy context and development. For this reason, the European Commission has defined a set of important skills for the future bioeconomy (see Fig. 38.1). These skills are considered critical for profiles of bioeconomists who catalyse successful collaboration along diverse bio-based value chains, covering the bioeconomy's manifold sectors.

38.2.1 The T-Shaped Profile

The combination of discipline-specific knowledge, context-dependent sustainability competencies and the need to integrate multiple stakeholders in the bioeconomy gives rise to a

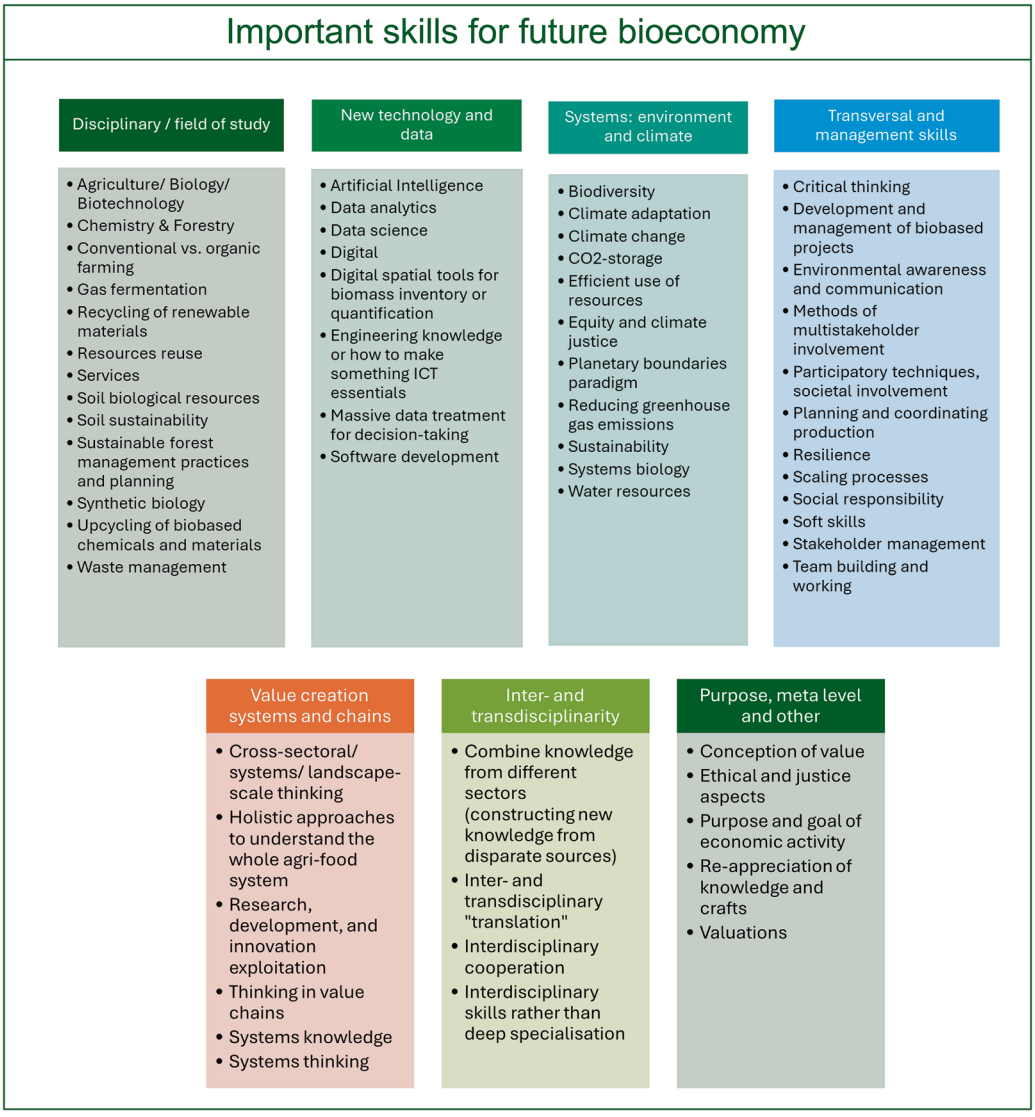


Fig. 38.1 Important skills for the (future) bioeconomy. (Based on European Commission 2022)

specific professional profile, the T-shaped profile, a term first coined by Marco Iansiti (1993). Metaphorically, the vertical stroke of the "T" symbolizes expertise or deep knowledge in a particular field or discipline. By contrast, the horizontal stroke represents integrative abilities, enabling T-shaped professionals to work effectively across disciplines and, in doing so, catalyse, manage and conduct contextualized research and innovation processes. These integrative abilities are based on extensive training in collaboration competencies. A professional with a T-shaped profile is aware of the variety of practices, approaches and methods employed by different disciplines or professions and understands their strengths and limitations.

The concept can contrast with the more traditional profiles of I- or A-shaped professionals (Fig. 38.2). Currently, most students graduate with an I-shaped profile, educated to become experts in a particular discipline. This means they have a high level of knowledge and expertise in their field of study. However, I-shaped professionals may be disadvantaged in conducting interdisciplinary team efforts. Deficits in understanding the fundamental ideas of other disciplines can hinder integration and communication with experts from other areas. In contrast, A-shaped professionals possess a high degree of expertise and knowledge in two areas, such as engineering and business, enabling them to connect at least two fields efficiently (Karjalainen et al. 2009).

The concept of T-shaped profiles goes a step further. These professionals are not only trained to work within multidisciplinary teams but also to facilitate collaboration and connections between experts with various backgrounds. This idea was initially derived from "integration teams" in "new product development", as it ideally contributes to more efficient innovation processes (Iansiti 1993). Originally, Iansiti (1993) emphasized the effectiveness of T-shaped profiles in fostering innovation through technology integration in the thriving high-tech sector of the 1990s.

Due to the diverse sectors and disciplines the bioeconomy encompasses, the T-shaped profile is designated to unlock the full potential of the bioeconomy. Players within the bioeconomy have to foster integrative approaches and common goals. Accordingly, intermediary bioeconomy professionals require a T-shaped profile, with expertise in a bio-based product-chain-related discipline and broad knowledge in associated disciplines (from primary production to commercialization, including processes, intermediates and products; see Parts II and III of this book). The ability to understand different scientific languages, by knowing their terminology and methods, enables the mediation between stakeholders and the facilitation of collaboration. This allows bioeconomists to form comprehensive frameworks for the collaboration of research or innovation teams with diverse backgrounds within the bioeconomic sector.

Various stakeholders interact within such frameworks. As a result, knowledge and skills are merged to address challenges. In this way, the frameworks serve as a roadmap for cross-fertilization and the generation of combinatorial innovations. This means that a set of

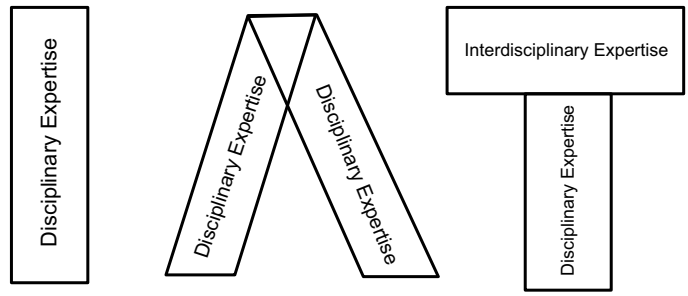


Fig. 38.2 Examples of different professional profiles. (Lask et al. 2018 licensed under CC BY 4.0. ▶ https://creativecommons.org/licenses/by/4.0/)

components may be combined and recombined in new ways to create cutting-edge approaches to (wicked) problems. For this, not only an inclusive and open culture are needed, but a common understanding of goals must also be developed. Therefore, an important task for T-shaped integration specialists is to ensure interdependence of individual goals within the group. Different stakeholders are likely to have different peers, ideas and approaches, meaning that overall team success may be influenced by individual research questions and norms. To achieve this, it is necessary to contextualize and assess the systemic impact of individual actions and knowledge and adjust these goals to the scope of the comprehensive framework. Therefore, integrative professionals in the bioeconomy have to be able to think strategically, requiring a goal-oriented and long-term perspective that has to be in alignment with different disciplinary views and practices. This profile description of a bioeconomist may sound fairly straightforward. In reality, the profiles and roles of bioeconomy professionals are highly diverse. Due to the vast size of the bioeconomic sector, there are numerous education and career paths, and no one-fits-all profile of a bioeconomist exists.

38.3 Education for the Bioeconomy: Approaches and Challenges

Traditionally, most higher education programs, especially university programmes, are designed to develop an I-shaped profile (Repko et al. 2016). Graduates gain profound expertise in one discipline with a specialization in a particular research field. During the last decade, education programmes with interdisciplinary curricula have been established, especially in the field of sustainability science, which places emphasis on interdisciplinary research. Bioeconomy is an excellent example of an interdisciplinary research field and is therefore well-suited for such interdisciplinary education programmes. Integrated disciplinary expertise from various knowledge domains connected to the bio-based value chain benefits the understanding of the challenges within the bioeconomy and supports designated bioeconomy professionals to develop a T-shaped profile.

In general, interdisciplinary study programmes combine two or more academic disciplines. Students acquire knowledge in these disciplines, learning methods, concepts and theories, as well as their integration and application to complex research problems, within interdisciplinary teams (Repko et al. 2016). In these teams, shared group processes, differing opinions and approaches are not only tolerated but appreciated (Barth and Burandt 2013). Repko et al. (2016) define interdisciplinary studies as "a cognitive process by which individuals or groups draw on disciplinary perspectives and integrate their insights and modes of thinking to advance their understanding of complex problems with the goal of applying the understanding to a real-world problem" (Repko et al. 2016).

Acquiring the ability to integrate and collaborate is key to the development of interdisciplinary competencies (Repko et al. 2016) and, thus, a main objective of education programmes for the bioeconomy. The programmes are intended to impart multidisciplinary knowledge and facilitate the development of interdisciplinary competencies through collaborative curriculum design and innovative learning environments. However, at the university level, the coordination of a collaborative curriculum means that established disciplinary structures need to be overcome.

The majority of interdisciplinary education programmes already established in the field of bioeconomy are master programmes (► Excursus 38.3). With a view to the development of a T-shaped profile, a completed disciplinary bachelor's degree would be beneficial. Disciplinary expertise (the vertical stem of the T) already acquired at the bachelor's level can be extended by interdisciplinary expertise (the horizontal bar of the T) in postgraduate studies. Additionally, students from different cultural and academic backgrounds create an international and interdisciplinary atmosphere, which facilitates the learning process. However, the students' diverse academic

backgrounds are also part of the challenge. The first step of an interdisciplinary education programme is to establish a common ground by addressing knowledge gaps. In the case of the MSc Bioeconomy programme at the University of Hohenheim, students learn natural science concepts, the basics of agricultural production and fundamental economic principles during the first semester.

After a common ground has been established, the focus shifts to the central topic: the bioeconomy. At the University of Hohenheim, students learn what the bioeconomy entails, why it presents both opportunities and challenges and how the transition towards a bioeconomy can be managed. The concept of bio-based value chains, along with the basics of bio-based resources, processes and products within these chains, is taught. There is also an open curriculum that enables students to develop their own individual profile.

Ideally, these profiles should draw on the large set of potential skills that are defined by the EU (see ◘ Fig. 38.1). It is important to emphasize that a single individual cannot encompass all aspects outlined therein. For this reason, a focused approach can be advantageous. The ideal typology of change agents suggested by van Poeck et al. (2017) may serve as a valuable starting point for considering effective combinations and profiles tailored to the intended role.

As part of the learning process, it is essential to develop a learning culture that is associated with open learning environments, where learning occurs in diverse forms and aligns with individual learning styles. This is an integral part of the learning process, because competencies are seen as learnable but not teachable (Barth and Burandt 2013). Already in 2007, Barth et al. (2007, p. 4) promoted a new learning culture which is "enabling-oriented, based on self-organization and centred on competence" with the following three key principles (Barth and Burandt 2013):

- **Self-directed** learning encourages intrinsically motivated learning. For example, project-based learning or e-learning emphasizes the active acquisition of knowledge. This approach accounts for students' varying education levels and learning speeds. Light supervision can guide students towards learning goals.
- **Collaborative** learning fosters participation and empathy. Group project work, in particular, supports the development of interdisciplinary competence.
- **Problem-oriented** learning addresses real-world problems. The first two principles are essential prerequisites for the successful application of this approach, often involving collaboration with external stakeholders (e.g. companies).

In the context of learning competencies, the interplay between formal and informal learning settings is of particular value (Barth et al. 2007). Study courses with open learning environments provide numerous opportunities for learning within a formal framework. However, informal settings, such as volunteering in a student group, also contribute to the personal learning process and competence development. Here, learning is self-directed without the assistance of an educator. In some settings, learning may even be incidental, with no prior intention to acquire knowledge, yet a clear awareness of having learnt something afterwards. The social dimension of informal learning further enhances competence development (Schugurensky 2000). Whether formal or informal, the proactive shaping of a T-shaped profile is a unique selling point for graduates. The innovative potential of the bioeconomy calls for forward-looking collaboration specialists, driven by the goal of the transition towards a bio-based economy.

In addition, a range of extra-curricular offers dedicated to the bioeconomy is available. Some examples are:



Fig. 38.3 Examples of bioeconomy job profiles. (Based on European Commission 2022)

Excursus 38.3 Examples of Study Programmes in the Field of the Bioeconomy

Over the last decade, various study pro grammes dedicated to the bioeconomy secto have been developed, including Europe's firs Bioeconomy degree programme at the Uni versity of Hohenheim (MSc Bioeconomy) Other examples include the MSc Biobased Sci ences (Wageningen University), MSc Biobase(Materials (Maastricht University), M.Sc. Bio economy (University of Greifswald), MS(Biological resources (Rhine-Waal Universit of Applied Sciences), MSc Management o Bioeconomy, Innovation and Governanc (University of Edinburgh), M.Sc. Bioeconomy Biotechnology and Law (International Helleni University) and BSc/MSc Bioeconomy (Tech nical University of Munich). Some common features among these programmes are the interdisciplinary approach, for example, through the study of entire bio-based value chains and the emphasis on sustainability (the ecological, social and economic impacts of bioeconomic developments). Their overarching goal is to educate professionals who can identify and develop innovation opportunities through the integration and collaboration of multi- and interdisciplinary perspectives and diverse knowledge sources. To this end, interdisciplinary problem-based group work activities are a prevalent feature of these programmes and their curricula.

- The European Bioeconomy University (EBU) offers the EBU Label, a certification programme designed for master's students enrolled in bioeconomy-related study courses. This programme aims to enhance and integrate existing disciplinary master's curricula by fostering interdisciplinary understanding and equipping students with knowledge of related disciplines and their scientific terminology, alongside their specialized expertise.
- FOEBE+, an EBU project that aims at equipping bioeconomy students at master's and PhD levels with tailor-made sustainable entrepreneurship skills.
- MOOC "Concepts of Sustainable Bioeconomy" developed by the University of Hohenheim as part of the project ABBEE (Accelerating the transition towards the Bio-Based Economy via Education).

The focus of this chapter is higher education. However, it is important to highlight that there are also educational offers for other target audiences. For example, games or books for children aim at inspiring, engaging and educating young minds through interactive activities. There are also courses, Massive Open Online Courses (MOOCs), talks and other formats of education that intend to upskill or reskill lifelong learners, industry representatives, policymakers and other professionals or individuals.

Educating for the bioeconomy involves solving different challenges. The design of interdisciplinary, updated and flexible curricula requires balancing a diverse set of expertise and be aligned with industry needs. This usually means practical and real training formats that might involve additional investments and preparations.

Another challenge is the regional differences of the bioeconomy. Due to the context-dependent nature of bioeconomy development and implementation, the education needs vary from region to region. Consequently, they require to be supported by work experience in the selected field and by connections with regional stakeholders.

Finally, professionals in the bioeconomy might need to maintain themselves updated due to the rapid advances in the field. This means that a promotion, access and expansion of educational opportunities within lifelong learning is essential.

38.4 Bioeconomists and Career Paths

With an ongoing transition towards a bioeconomy, a significant number of employment opportunities are expected to emerge in the coming years. The European Commission anticipates a diverse range of future bioeconomy job profiles (see Fig. 38.3). Focusing on high added value and the creation of new economic activities, the bioeconomy demands skilled professionals across the bio-based value chains. Firstly, bioeconomists play a crucial role in establishing and organizing value chains, requiring key competencies such as those outlined in this chapter (horizontal stroke of the T). Secondly, the various stages within these value chains necessitate distinct types of disciplinary expertise (vertical stroke of the T).

As discussed in this and preceding chapters, the "added value of the bioeconomy lies in its potential to create synergies through collaboration between various sectors, both along and across the value-chains", fostering opportunities for innovation (European Bioeconomy Stakeholders Manifesto 2017, p. 5). Building on this, bioeconomy practitioners and researchers equipped with key competencies serve as connectors and catalysts within the bioeconomy. These roles are often performed in managerial and leadership positions across private, public and third-sector organizations, encompassing fields such as research and development, rural development, advisory services, sustainability-oriented institutions and policy-making bodies. A distinctive role for bioeconomists, attributed to their T-shape profile, is the leadership of interdisciplinary teams and projects, exemplifying the position of a project manager in the context of bioeconomy.

Due to the relative novelty and interdisciplinarity of bioeconomy education programmes, there is no empirical information on the positions that are held by bioeconomists. Per se, their versatile skill sets are highly relevant and beneficial beyond the immediate context bioeconomy. Consequently, career opportunities arise across a wide range of sectors and industries.

After 10 years of bioeconomy education, some insights can be provided on possible career paths. In general, it can be summarized that Hohenheim Bioeconomy graduates tend to work as sustainability managers, sustainability analysts and innovation managers. They work in various sectors (mainly food, feed & biotech, but also more general such as consulting and auditing), in research institutions and private industry alike. A significant proportion of graduates have explored career opportunities in start-ups, recognized as key drivers of innovation within the bioeconomy.

In order to give more tangible insights on possible career paths, this chapter ends with four exemplary perspectives of former graduates of the bioeconomy master's programme in Hohenheim (See ▶ Excursus 38.4). They give insights on how they perceived bioeconomy study course and where it has taken them. In addition to these examples, more possible roles of bioeconomy change agents can be explored in the ▶ biopioniere section of the biooekonomie.de.

Excursus 38.4 Voices of Bioeconomy Graduates

Ariana Alva Ferrari: "As a student from Peru joining the Bioeconomy Master's programme at the University of Hohenheim was both an exciting and life-changing experience. While I had always been passionate about sustainability, the program expanded my understanding of the broader implications of bioeconomic systems. Initially, my goal was to master the sustainable use of resources, but as I immersed myself in the curriculum, I came to appreciate how profoundly food—what we eat and how it's produced—shapes the health of our planet".

Studying during the pandemic presented unique challenges but also brought together an ambitious group of students from around the world, each with distinct backgrounds and expertise. Learning alongside individuals with firsthand experience in agriculture, natural sciences and food systems—and hearing their diverse viewpoints—shaped my understanding of the importance of considering every step of the value chain, from raw materials to finished products. This experience deepened my ability to critically assess the social, economic and environmental impacts of sustainability.

The programme extended beyond the classroom, connecting us to a dynamic ecosystem of real-world innovation. Through its partnership with EIT Food, an initiative supported by the European Union, I engaged with the broader EU innovation community. This fostered collaboration among students, researchers and policymakers to address global challenges. Within this vibrant environment, I realized my vision: a product with the potential to revolutionize plant-based eating.

This journey led to the creation of Viva la Faba—a plant-based cheese startup harnessing the power of beans. Reflecting on this experience, I realize the programme gave me more than an education—it was empowering, and I feel privileged and grateful for this transformative journey".

Gabriel Arbonès: "The Master of Bioeconomy allowed me to specialise in different aspects of the green economy, studies that in 2017 were not easily available in my home country, Spain. The Master's is designed to give the freedom to choose all the courses offered by the University, which was crucial for me to choose a path of study that I am still following now in my PhD research. All the courses related to agriculture and ecosystems, as well as the knowledge of how to conduct scientific research, have been the basis for me to continue my research on these topics".

I also had the opportunity to work as a research assistant during my MSc, which allowed me to gain practical experience in research, such as designing and managing experimental sites and analysing data. The flexibility of the Master's also allowed me to do an internship in a consultancy working on carbon market projects in Latin America, which marked my first professional experience in the Bioeconomy and gave me the professional experience to continue working on climate change mitigation projects.

In conclusion, the Master of Bioeconomy has given me the opportunity to specialize in other aspects of sustainability while broadening my vision. It has given me the academic foundation to pursue a PhD in the field of agriculture and sustainability, as well as the opportunity to gain valuable scientific experience as a research assistant and professional experience in the industry.

Christoph Spenger: "Looking back, I am grateful for having studied the master's in Bioeconomy since it has been a great starting point for my career in sustainability".

On the one hand, the "vertical" part of the T-shaped profile has enabled me to set my own focus: During my studies, I have developed a great interest in Life Cycle Assessment (LCA) methodologies. In this context, the programme's high flexibility has enabled me to complement my theoretical knowledge gained from lectures with practical experiences from an internship and finally with a self-selected master's thesis about LCA in the automotive industry. Upon entering the job market, I found that these skills are highly sought after and provide a strong foundation from which I could branch into related fields (e.g., climate strategy or sustainability reporting).

Additionally, I have increasingly recognized the value of the master's emphasis on interdisciplinary work, as this reflects what I encounter in my professional life. Sustainability-related projects often involve various departments of an organization. To develop an effective solution, it is, therefore, necessary to get a good understanding of different viewpoints. For instance, when developing a climate-strategy for an organic brewery, I needed not only to align internally (e.g. with energy management) but also with actors across the value chain (e.g. organic farmers). Thus, the horizontal stroke of the "T" has proven to be very helpful (e.g. by gaining a basic understanding of agricultural production).

Last but not least, sustainability is a rapidly evolving field in which it is virtually impossible to "know everything in advance". In this regard, the programme is a great opportunity for peer-to-peer learning–both during the studies and beyond."

Ernesta Maciulyte: "The Bioeconomy programme offers a diverse range of subjects and opportunities for individuals from various backgrounds to gain valuable insights into sustainability. For me, the programme was instrumental in diversifying my skill set, building on my economic background, and enabling me to work in fields such as nature-based solutions, climate finance, and sustainability consulting. While it is not a highly specialized master's degree, the programme provided me a strong foundational knowledge that I could further develop through targeted internships and professional experiences".

Questions

1. What is the role of a bioeconomist, and why is collaboration considered a central aspect in this role?
2. What are the skills and competencies that a bioeconomist need?
3. What are the approaches for bioeconomy education at higher education level?

Answers

1. A bioeconomist is a catalyser and a change agent able to manage and implement activities that support the transition towards a sustainable bioeconomy. This transition is a cross-cutting, iterative and adaptive endeavour that promotes both technological and social progress and innovation, and therefore, it is consider a wicked problem. Consequently, the bioeconomist has the role to facilitate collaboration to solve this wicked problem through the integration of various views and perspectives under a systems approach.
2. First, a bioeconomist needs sustainability competencies. These are systems-thinking competence, anticipatory competence, normative competence, strategic competence, interpersonal competence, intrapersonal competence, integration competence and implementation competence. These skills and competencies need to be complemented by context-specific disciplinary competencies. This means that bioeconomists need to possess knowledge of bioeconomy-related skills. They are expected to be specialized in one field but also able to understand the scientific language of associated disciplines relevant to the bioeconomy context.
3. The bioeconomy is an example of an interdisciplinary research field and is therefore well suited for such interdisciplinary education programs. Students acquire knowledge in different disciplines, learning methods, concepts and theories, as well as their integration and application to complex research problems, within interdisciplinary teams. In this context, differing opinions and approaches are appreciated, and applying the understanding to real-world problems is essential.

   The programmes, then, intend to impart multidisciplinary knowledge and facilitate the development of interdisciplinary

competencies through collaborative curriculum and open and innovative learning environments. However, at the university level, the coordination of a collaborative curriculum means established disciplinary structures need to be overcome.

Most interdisciplinary master's programmes already established in the field of bioeconomy focused on the development of a T-shaped profile. The usual first step of an interdisciplinary education programme is to establish a common ground among students by addressing knowledge gaps. And after a common ground has been established, the focus shifts to the central topic: the bioeconomy. The curriculum needs to be open to enable students to develop their own individual profile. Open learning environments should follow a self-directed, collaborative and problem-oriented approach.

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Guiding the Bioeconomy Transition

Sustainability is a guiding principle of the bioeconomy. However, the bioeconomy is not sustainable per se, and guidelines and methodologies are required to steer the transition towards a future-oriented and sustainable bioeconomy. For this purpose, this part of the book includes reflections on a responsible bioeconomy and possible synergies, trade-offs and interactions between biodiversity and the bioeconomy. Methodological approaches from three areas are elaborated as follows: (1) sustainability assessment in the bioeconomy, including environmental, economic and social assessment methods; (2) modelling, scenario analysis and integrated model approaches and (3) bioeconomy monitoring, which is relevant for informing decision-making processes that shape the transition to a sustainable bioeconomy.

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Conditions for a Responsible Bioeconomy

Markus Vogt



Fig. 39.0 Conditions for a responsible bioeconomy (generated with DALL-E 2024) (► https://doi.org/10.1007/000-hvm)

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The term "bioeconomy" is ethically demanding, but at the same time dazzling, ambiguous and open to interpretation. If it is not to become an ethically ambivalent or even totalitarian paradigm, certain conditions for its interpretation and implementation must be met. For example, it is only responsible if the various dimensions of nature's value are protected by appropriate standards and strategies, if it is strictly aligned with the guiding principle of sustainability, if it takes planetary boundaries into account, and if it keeps an eye on the ambivalences of the green growth promises. This chapter describes how a responsible bioeconomy avoids a one-sided focus on (linear) maximisation and pays more attention to systemic interactions as well as the goals of waste prevention and circularity. It incorporates socio-economic and environmental issues such as the protection of and fair access to soil, water, seeds, and regional food markets into its hunger reduction strategies. The bioeconomy must be underpinned by the concept of "responsible innovation", which includes technical solutions as well as socio-cultural, environmental and regulatory aspects. As a knowledge-based concept focused on innovative research and development, a responsible bioeconomy can develop the dynamic side of sustainability.

Learning Objectives

After studying this chapter, you will…

- …be able to criticise a narrow understanding of bioeconomy which is not sustainable (see ► Sect. 39.1).
- …be able to explain the term "responsible innovation" (see ► Sect. 39.2).
- …be able to define some conceptual, ecological and social criteria for a responsible bioeconomy (see ► Sect. 39.2).

39.1 The Ethical Ambivalence of Bioeconomy

The bioeconomy has a high ethical claim: It stands for an approach that overcomes superficial opposites and polarisations between ecology and economy, of nature and technology, of preservation and design, renunciation and innovation. It makes use of the specific technical, economic and innovative aspects of sustainability. In this respect, it is a key to the process of implementing the goals of sustainability in scientific research, engineering and economics (Vogt and Frankenreiter 2022).

At the same time, however, the bioeconomy is a highly ambiguous and dazzling concept with very different origins and understandings. The extent to which ecological responsibility and economic success can be reconciled should, therefore, be critically examined. Sometimes the reconciliation of ecology and economy is just wishful thinking and a semantic illusion due to the ambiguity of the term and the harmonising concealment of conflicts (Henkel et al. 2023).

Franz-Theo Gottwald and Anita Krätzer, for example, have criticised the bioeconomy as a "totalitarian paradigm" (Gottwald 2014). In their understanding, the bioeconomy represents a new level of quality in the economic exploitation of nature, and thus an absolutisation of economic thinking as well as an industrial-technological model for agriculture and food, which are the most important application areas of the bioeconomy. According to the interpretation of Gottwald (2014), the bioeconomy, as advocated by the E.U. level and the German government, is about the "conversion of all living things into the raw material biomass" (Gottwald 2014, p. 6 [own translation]). A 2015 study by the World Food Institute comes to a similar conclusion (Gottwald and Budde 2015). In particular, the ethical assessment of synthetic biology, which not only uses living organisms but also technically produces them, is regarded as highly controversial (Grefe 2016; oekom 2020).

The bioeconomy is closely linked to the concept of the "green economy". As a promise of a win-win situation between economy and ecology, it has contributed significantly to the rhetorical acceptance of the sustainability concept at the E.U. level. However, the price was high: acceptance was paid with a reinterpretation of sustainability in terms of "green growth". In Germany in particular, the supposed "green economy" is therefore heavily criticised by ecologically oriented institutions and blamed for the glaring discrepancy

between the promises and reality of global climate and environmental policy over the past two decades (Fatheur et al. 2015). In their view, the concept understates the extent of the necessary change in direction and needs to be deconstructed through a discourse and power-critical analysis. They suggest that the bioeconomy is in part just a new label for genetic engineering in order to avoid the critique of this concept.

However, such critiques do not offer an alternative concept, so their practical value lies more in providing impetus for social science to accompany and develop the bioeconomy than in providing arguments for its blanket rejection. The basic idea of the bioeconomy, to replace fossil fuels with renewable raw materials and to develop and use new technologies for processing bio-based resources, cannot be ethically criticised (Lewandowski 2018; Vogt 2018; Morone et al. 2023).

There are fundamental conflicts in the bioeconomy discourse due to very different classifications of the concept, which are essentially the result of the fact that it originated in a research-technological context, but is now much broader and finds important fields of application in industrial policy as well as in the field of agriculture and nutrition (Grefe 2016; for some historical phases and actors in the rather polarised debate on the bioeconomy in the E.U. level, cf. Kiresiewa et al. 2019; Starke et al. 2023). As a result, the concept has undergone a socio-political expansion that requires ethical accompanying research on its premises, contexts, demarcations and effects (Vogt 2021, p. 557–560).

39.2 Conditions for a Responsible Bioeconomy

The conceptual openness and ambiguity of the bioeconomy make it necessary, from an ethical point of view, to define conditions and criteria for its responsible practice. These can also be described as ethical guidelines. By way of example, I would like to outline the following six aspects:

1. The bioeconomy must be guided by the principles of sustainability and sufficiency: According to the OECD guidelines, the bioeconomy should be the driving force behind sustainable production, improving the world's food supply, climate protection and solving many environmental problems (cf. OECD 2009, p. 5). In most publications on the bioeconomy, however, "sustainable" is used adjectivally as a decorative term without any substantial explanation. However, if this quality standard is not to remain an empty, non-binding phrase, the bioeconomy must be conceived in terms of sustainability criteria (Vogt 2018; Vogt 2024, p. 313–336). It is not uncommon for the bioeconomy to be subsumed under the heading of "green growth". However, sustainability also requires a discourse on sufficiency and the limits of growth (Grefe 2016; Vogt 2021, p. 147–183).
2. The ethics of the bioeconomy includes criteria of risk minimisation and resilience: An ecologically responsible concept of the bioeconomy requires an explicit discourse on risk, which has so far only been developed in an abstract and defensive way in the context of the bioeconomy. The principles of prevention and risk minimisation should be systematically reflected (Renn 2008). It is not possible to avoid all risks; on the contrary, innovations in the bioeconomy are always associated with risks. However, these must be assessed systematically, which can also be described as "risk maturity" (Vogt 2021, p. 412–419). Resilience, as robustness in the face of change, is a suitable concept for avoiding irresponsible risks. Resilience can be seen as a new measure of progress (Vogt 2021, p. 427–444). Particularly in the area of food security, which is central to the bioeconomy, the concept of resilience (Vogt 2021, p. 427–444) leads to a paradigm shift: the critical factor in the global South is not primarily the quantity of food, but rather the purchasing power and thus access to local food markets and, above all, to land for cultivation. Under the conditions of climate change, the transition to more drought-resistant crops and access to

water are also becoming increasingly important.

3. The concept of the bioeconomy is only responsible if it protects the different value dimensions of nature through appropriate standards and strategies: Precisely because the bioeconomy is a highly innovative field of new dimensions of knowledge and ways of using nature (Lagioia et al. 2024), it needs a clear and binding value base. Values have different dimensions: for example, there are exchange values (functional and purposeful), aesthetic values (depending on different subjective perceptions) and existential values (something that is valuable for its very existence). Moral values are defined by the fact that they refer to a good or something good to be sought for its own sake. There are different categories of moral values, e.g. categorical values, i.e. values that cannot be weighed or exchanged, and values that can be weighed, between which a compromise must be found in case of conflict (Vogt 2014). The bioeconomy can only be responsible if, in addition to economic and functional values, it also takes into account the intrinsic value of animals, plants and landscapes (Vogt 2024, p. 253–336). In the field of animal, soil, water and landscape conservation, for example, it must progressively protect the different value dimensions of nature and its development conditions as a complex network of ecological system contexts through appropriate standards and strategies. It needs an ethical framework of standards for environmental and social compatibility and animal welfare.
4. The bioeconomy should apply the concept of planetary boundaries to identify priorities for nature and environmental protection, with a stronger focus on ecological resilience strategies: The concept of planetary boundaries, developed by a group of earth system and environmental scientists led by Johan Rockström (Stockholm Resilience Centre) and first published in 2009, defines nine indicators of planetary boundaries that must not be crossed if equitable, safe, robust, crisis-resilient and sustainable development is to remain possible (Rockström and Gaffney 2021). In addition to the well-known issue of climate change, the concept emphasises the importance of protecting biodiversity, the natural nitrogen cycle, and water and land resources (Richardson et al. 2023). The protection of planetary boundaries contrasts sharply with the massive and expanding use and destruction of wildlife habitats and resources in the current global economy. The bioeconomy is only credible if the "bio" in its name is filled with specific ecological relief strategies, especially in the field of land management (e.g. less and/or more efficient use of artificial nitrogen and phosphorus fertilisers in agriculture, as well as in the field of landscape restoration and natural landscape conservation).
5. It's ethically crucial to recognise that there is no "one-fits-all bioeconomy": There is no single bioeconomy approach for all regions of the world. For example, food security in many countries of the global South requires greater support for smallholder farmers and, at the same time, less capital-intensive forms of agriculture (Deutsche Kommission Justitia und Pax 2010). The need for resilience (e.g. to drought, heat, floods, certain pests) or consumer acceptance of innovative products such as meat substitutes varies greatly from region to region.
6. The bioeconomy needs an ethics of responsible innovation: To develop the potential of research and development, the bioeconomy requires an ethics of responsible innovation (Bogner et al. 2015; Lagioia et al. 2024). Responsible innovation (RI) is a way to solve scarcity problems in a knowledge-based, offensive, creative and risk-sensitive way. An ethically responsible bioeconomy will have to be measured by the extent to which it is possible to effectively protect fertile soils, clean water, forests and a stable climate (to name but a few examples) as elementary assets of the world's common good. Ethics can be a fundamental extension of the bioeconomy's horizon, helping to provide it

with the necessary normative and regulatory basis. The bioeconomy operationalises the innovative side of sustainability by strategically tapping renewable resources and consistently avoiding waste (Braungart and McDonough 2009). A bioeconomy understood in this way creates technical, socio-cultural and political transformations in order to integrate economic processes into ecological cycles and regeneration processes. It combines the diverse innovation potentials of different actors and fields of action with regard to the ethical goals of a just and environmentally friendly society. A socio-culturally expanded, ecologically sound and regulated innovation ethic is suitable as the strategic core of the bioeconomy (Vogt and Frankenreiter 2022). The bioeconomy aims at a combination of technical, social, economic and political intelligence. These will be the criteria by which future progress will be measured.

Questions

1. What different types of values does a responsible bioeconomy need to take into account?
2. How can the bioeconomy drive responsible innovation?

Answers

1. There are exchange values (functional and purposeful), aesthetic values (depending on subjectively different perceptions) and existential or moral values (something that is valuable for its existence and for its own sake).
2. The bioeconomy operationalises the innovative side of sustainability by strategically tapping renewable resources and consistently avoiding waste. A bioeconomy understood in this way creates technical, socio-cultural and political transformations to integrate economic processes into ecological cycles a regeneration processes.

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Exploring the Biodiversity–Bioeconomy Nexus

Arndt Feuerbacher, Ricardo Vargas-Carpintero, Jan Weik, and Valentin Schlecht

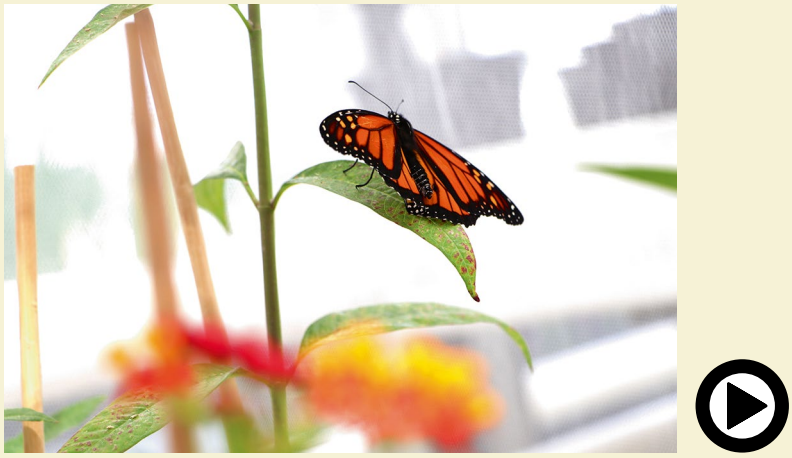


Fig. 40.0 Exploring the biodiversity–bioeconomy nexus. (© Universität Hohenheim, Corinna Schmid) (► https://doi.org/10.1007/000-hvn)

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This chapter explains how biodiversity and the bioeconomy are interrelated and how the bioeconomy depends on healthy and intact biodiversity. It does so by briefly defining biodiversity and describing the main metrics used to measure it. The links between biodiversity and the bioeconomy are then explored by examining the direct drivers of biodiversity loss, and in the context of the ecosystem services framework. This allows the possible synergies and trade-offs between biodiversity and the bioeconomy to be described and understood. Finally, it highlights the role of policies and technologies in promoting a sustainable bioeconomy that also benefits biodiversity.

Learning Objectives

After studying this chapter, you will…

- …be able to explain what biodiversity is and to describe the main metrics used to measure it (see ► Sect. 40.2).
- …be able to describe the interrelationship between biodiversity and the bioeconomy, including the drivers of biodiversity decline and the role of ecosystem services in supporting the bioeconomy (see ► Sects. 40.5 and 40.9).
- …be able to explain the potential synergies and trade-offs between biodiversity and the bioeconomy (see ► Sect. 40.9).

Biodiversity and bioeconomy share the same prefix "bio", the short form of biology, which is the scientific study of living organisms. Both concepts have become established terms in the recent past. The scientist Thomas Lovejoy first introduced "biological diversity" to a broader scientific audience in 1980 through his foreword for a book on conservation biology (Soulé 1980). The compound word "biodiversity" was then first consciously coined in 1985 by Walter G. Rosen.

The word "bioeconomy", as described in ► Chap. 2, has globally been embraced as a policy concept. The bioeconomy is hereby increasingly gaining in relevance as a potential pathway to reconcile conservation and regeneration of nature with socio-economic advancement as can be seen in the newest definition of the bioeconomy of the IACBG (see ► Sect. 2.3.4.4).

The different possible shapes of transitions (see ► Chaps. 2 and 3) towards a bioeconomy can hereby have different effects on biodiversity.

40.1 What Is Biodiversity?

There are many definitions of biodiversity. Most known is the definition from the Convention on Biodiversity in 1992.

> Biodiversity is the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems.

Another definition is provided by DeLong (1996) which states that

> Biodiversity is a state or attribute of a site or area and specifically refers to the variety within and among living organisms, assemblages of living organisms, biotic communities, and biotic processes, whether naturally occurring or modified by humans.
>
> Biodiversity can be measured in terms of genetic diversity and the identity and number of different types of species, assemblages of species, biotic communities, and biotic processes, and the amount (e.g. abundance, biomass, cover and rate) and structure of each.
>
> It can be observed and measured at any spatial scale ranging from microsites and habitat patches to the entire biosphere.

This definition shows how broad the concept of biodiversity is. It encompasses the diversity within and across multiple dimensions.

Excursus 40.1 Alpha, Beta and Gamma Species Diversity

Whittaker (1972) described three terms for measuring species diversity over spatial scales: alpha, beta and gamma diversity. Alpha diversity refers to the diversity within a specific site area or habitat. It is typically quantified using measures such as species richness or diversity indices (e.g., Shannon or Simpson) (see Table 40.1). Beta diversity measures the change in species composition between different sites or ecosystems (i.e., species turnover). Gamma diversity is a measure of the overall diversity across all sites or habitats in a region or landscape. The concepts of alpha, beta, and gamma species diversity are widely applied in ecology, conservation and environmental management (Lüttge et al. 2020; Socolar et al. 2016). Since species diversity is a main component of biodiversity, these measures are used as biodiversity measures.

Table 40.1 Overview of alpha, beta and gamma biodiversity measures

Measure	Definition	Scale	Key focus	Example
Alpha diversity	Species diversity within a specific site or sampling unit.	Local (within-site)	Species richness and evenness at one site.	Number of plant species in a forest patch.
Beta diversity	Turnover or dissimilarity in species composition between sites or habitats.	Between sites (across any scale)	Turnover or similarity of species between areas.	Comparing bird species in two adjacent wetlands.
Gamma diversity	Total species diversity across all sites or habitats in a region.	Landscape/ Regional	Overall species richness of the region.	Total diversity of plant, bird and insect species in an entire forested region.

The early definitions of biodiversity, such as the one by the Convention on Biodiversity, rather focused on the diversity at the three main biological organizational levels (genetic diversity, organismic diversity and ecological diversity). However, these levels are hardly separable from each other (Härdtle 2024). For example, a reduction in habitats does not only reduce ecological diversity, it also has impacts on both the organismic and genetic diversity (ibid). A simplified view on biodiversity is limited to measuring the richness and diversity at each organizational level. Yet, this would neglect many other factors that are not adequately reflected in these metrics, such as the interactions between species, nutrient cycles or dynamic processes within ecosystems (Härdtle 2024). To account for this complexity, Noss (1990) proposes that biodiversity should also be measured and monitored across the three spheres of compositional, structural and functional diversity as presented in Table 40.2.

Noss (1990) comprehensively describes the different available indicators for measuring and monitoring biodiversity for each combination of organizational level and biodiversity attribute presented in Table 40.2. Knowledge and practices in this regard have advanced substantially since then, for instance by using methods based on artificial intelligence or citizen science (e.g. van Klink et al. (2024) describes a toolkit for global insect biodiversity monitoring.) While a detailed description of such new methods goes beyond the scope of this chapter, the next subsection introduces established biodiversity indicators and metrics.

Table 40.2 Biodiversity attributes across different biological organizational levels. Example metrics and indicators for each attribute are provided

Biological organizational level	Biodiversity attributes		
	Compositional diversity	Structural diversity	Functional diversity
Regional-level landscape	Landscape types (e.g. proportions of different habitat and landscape types)	Landscape patterns (e.g. heterogeneity, fragmentation, connectivity)	Landscape processes (e.g. disturbance processes such as wildfires or floods)
Community-level ecosystem	Composition of communities/ecosystems (e.g. diversity of species and guilds, evenness)	Physiognomy and habitat structures (e.g. openings and gaps in forest canopy)	Ecosystem interactions and processes (e.g. trophic interactions or human use and disturbance)
Population–species	Composition of species and populations (e.g. absolute and relative abundance of species)	Population structures (e.g. information about distribution and range such as age distribution)	Demographic processes, life cycles (e.g. population fluctuations)
Genetic level	Composition of genes (e.g. allele diversity, heterozygosity)	Genetic structures (e.g. effective population size)	Genetic processes (e.g. inbreeding depression, mutation rates, gene flow)

Adaptation from Härdtle (2024), Noss (1990) and Schulze et al. (2019)

40.1.1 How Is Biodiversity Measured?

Of all three biodiversity attributes (Table 40.2), compositional diversity is arguably most intuitively linked to the common perception of biodiversity. According to Duelli and Obrist (2003), it can also be considered the most common indicator to measure biodiversity. Moreover, even though the definitions of biodiversity are far more comprehensive, we can for simplicity say that species are "the units of biodiversity" (Claridge 1997, cited in Duelli and Obrist 2003). Only focusing on compositional diversity of species also indirectly includes structural and functional diversity, because of their mutual dependency (Duelli and Obrist 2003).

To measure compositional diversity, we rely on metrics and indicators (see ▶ Sect. 41.1.2). The *abundance* of a species is a metric that quantifies either the number of individuals of that species or, alternatively, its biomass. Another simple measure is the *species richness*, which is the number of different species in a specific region. Both species abundance and species richness are the most applied metrics used in ecology literature, conservation planning and the biodiversity offsetting sector (Marshall et al. 2020). However, both metrics oversimplify the complex nature of biodiversity. They do not indicate how evenly individuals are distributed among species—an aspect captured by measures of species evenness. They may also ignore temporal and spatial variability when data are collected at only a single point in time or location. They do not capture the functional role of specific species within an ecosystem, which may be crucial for the healthy functioning of the overall ecosystem. And, while there are certainly more weaknesses, they lastly overlook the dimension of genetic diversity, which is crucial for maintaining a healthy population that is adaptable and resilient to environmental changes.

Species abundance values form the basis for calculating species evenness, which

Table 40.3 Overview of selected biodiversity indicators

Dimension	Metrics	Example
Species diversity	Species richness Species evenness Species diversity indices such as Shannon index or Simpson index	A specific coral reef in the Great Barrier Reef might host 300 species of fish, 100 species of coral, and 20 species of invertebrates. The species richness thus would be 420. If among the 300 fish species, 95% of individuals belong to one species, the species evenness is low. If all species are equally represented, evenness is high. A coral reef with high richness and relatively even species abundances might have an H' value in the range of 2.5–3.0, indicating high diversity.
Genetic Diversity	Allelic richness Heterozygosity Genetic distance	A population of African elephants may show high allelic richness if many different versions of certain genes occur within the population. If individuals display high heterozygosity at several genetic markers, this indicates greater genetic variability, which can reduce the risk of inbreeding. Comparing two elephant populations—one in Kenya and another in South Africa—may reveal a large genetic distance between them, reflecting limited gene flow and long-term separation.
Habitat Diversity and Quality	Ecosystem diversity Habitat extent and condition	The Amazon region contains a wide range of ecosystems, including tropical rainforests, flooded forests, and freshwater river systems, each supporting different species and ecological processes. Habitat quality can vary across this landscape: areas of intact forest generally support higher biodiversity, while degraded or fragmented patches tend to host fewer species and provide reduced ecological functions.

Adapted from Bartowski et al. (2015) with fictional examples

describes how similar the abundances of different species are within a community. This provides insight into how similar the population sizes of different species are within an ecosystem. A high evenness indicates a more balanced community structure, whereas a low evenness reflects dominance by a few species. Various indices have been proposed to quantify evenness. One of the most commonly used diversity indices is the Shannon Index (also known as the Shannon–Wiener Index), from which an evenness measure can be derived.

Table 40.3 introduces a selection of different indicators used for different dimensions of biodiversity.

Following from the definition above, biodiversity is a state that is observed at a given time

Excursus 40.2 Shannon index

The Shannon index, H, measures biodiversity by accounting for the total number of species, S, which is the species richness, and each species' population share, p_i.

$$H = -\sum_{i=1}^{S} p_i \ln(p_i) \tag{40.1}$$

If n_i is the number of individuals of species i, and N is the total number of individuals of all species, then the relative proportion of species p_i is calculated as:

$$p_i = \frac{n_i}{N} \tag{40.2}$$

across all biological scales as outlined in Table 40.2. In each scale, we can differentiate between compositional, structural and functional diversity for which a breadth of indicators and metrics exist.

Species richness, for instance, measures the number of species present in a certain location, while the species evenness describes how individuals are distributed among those species. Species abundance, by contrast, is only a headcount of the individuals of a particular species, and therefore captures only one narrow aspect of biodiversity. For example, we might observe 100 individuals of the common clownfish (*Amphiprion ocellaris*) in a specific area of the Great Barrier Reef. However, this indicator does not tell us anything about the diversity (or number) of species, which is captured by the metrics of species diversity mentioned in Table 40.3.

Finding an adequate biodiversity indicator is challenging. It is common practice to use different indicators at once to cover different dimensions of biodiversity (Schlecht et al. 2026).

There is no single indicator of biodiversity that is recognized as the best.

40.2 Biodiversity and Ecosystem Services

Biodiversity has a key role as a regulator of ecosystem processes. Conserving biodiversity is not only a means to an end of itself, but it is also crucial to ensure the well-functioning of ecosystems. Healthy ecosystems are vital not only for nature but also for humans because of the various ecosystem services they provide.

The interrelation between ecosystems and the benefits humanity receives from them can be best described using a third concept, the concept of "ecosystem services", which serves as a bridge to understand the nexus between biodiversity and the bioeconomy.

The Millenium Ecosystem Assessment defines ecosystem services as "the benefits people obtain from ecosystems" (Millennium Ecosystem Assessment (Program) (Ed.). 2005, p.40). While the benefits from ecosystems dominate, ecosystems occasionally may also contribute disbenefits or losses to people, e.g. crop damage by wildlife or pests or calamities from falling trees (Zhang et al. 2007; Saunders 2020).

Beneficial ecosystem services are the result of complex ecological processes and interactions that sustain life and contribute to human well-being. They can be divided into four main categories: provisioning services, regulating services, habitat services and cultural services (de Groot et al. 2012). For an overview of ecosystem services see Excursus ▶ 6.4)

40.3 The Drivers of Biodiversity Decline

Globally, biodiversity is declining—a trend that, at least in the media, is primarily communicated by referencing the health of species' populations (e.g. the IPBES report stating that one million species are threatened with extinction) or changes in populations of species or communities (e.g. the decline in insect biomass as found in the Krefeld study by Hallmann et al. 2017). There is a high variety of drivers behind the decline in biodiversity that are either direct or indirect. Direct drivers impact biodiversity directly and they have three sources (Díaz and Malhi 2022; (Millennium Ecosystem Assessment (Program) (Ed.) 2005). They can be anthropogenic, i.e. they are caused by humans, for instance through mining, deforestation, hunting, pollution or anthropogenic climate change. They can be caused by nature itself, as in the case of natural disasters such as volcano eruptions or extreme weather events. Or they can be a combination of both natural and human causes, such as the introduction of invasive species. In contrast, indirect drivers act diffusely. They influence one or multiple direct drivers of biodiversity decline, and they are characterized by a high interaction with other indirect drivers (Nelson 2005). The Millenium Assessment identifies demographic, economic, social, political, techno-

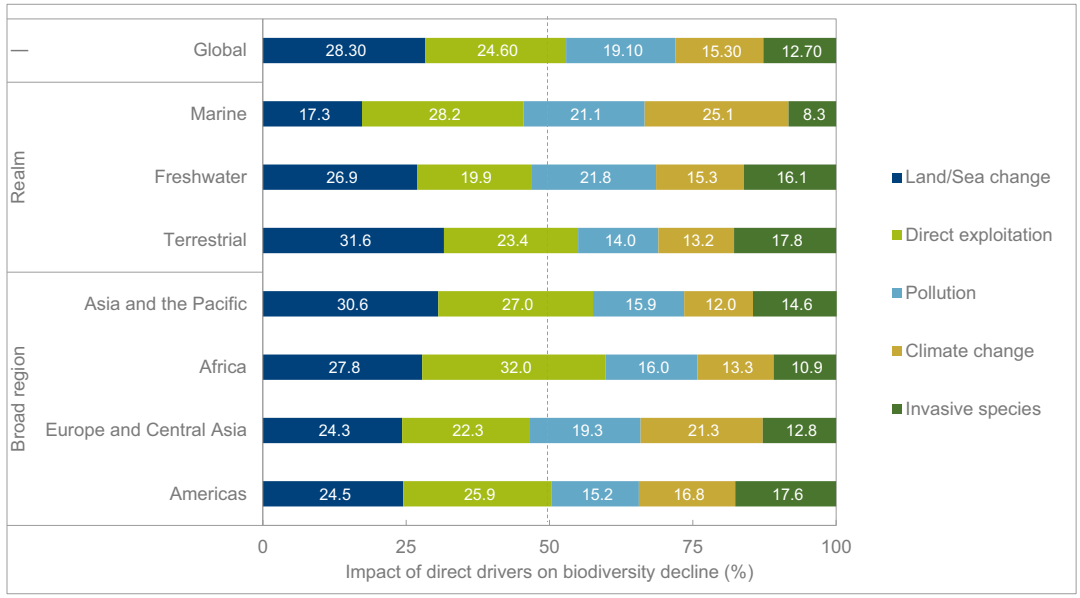


Fig. 40.1 Relative impact of direct drivers of biodiversity declines since the 1970s globally, by realm or by broad region (Own calculation based on Jaureguiberry et al. 2022)

logical, scientific, cultural and religious changes as indirect drivers (Nelson 2005) Following this definition, indirect drivers are thus predominantly anthropogenic; they are the result of how we humans live our lives on planet earth. Distinguishing between direct and indirect drivers is crucial when trying to mitigate their adverse impacts on biodiversity. There is little hope for success when biodiversity conservation efforts only focus on mitigating direct drivers if at the same time the underlying indirect drivers that are fueling the direct drivers remain neglected.

The direct drivers of biodiversity decline are manifold and interconnected. Recent research (Jaureguiberry et al. 2022; Caro et al. 2022) indicates that across terrestrial, marine, and freshwater ecosystems, two dominant direct drivers emerge: changes in the use of land and sea, and the direct exploitation of natural resources. These two drivers are estimated to be responsible for more than half of the global biodiversity decline since the 1970s (Jaureguiberry et al. 2022). Maybe surprisingly, pollution (including nitrogen pollution), climate change and invasive alien species rank behind these two drivers.

Figure 40.1 illustrates the relative contribution of the five main direct drivers to biodiversity decline at the global level, across terrestrial, freshwater, and marine realms and within four broad world regions. In the terrestrial realm, which is crucial for the bioeconomy, land changes are even more significant drivers than globally, across all realms. Land change refers to the increasing intensification of land use (e.g. increased use of agrochemicals, larger plot sizes and specialization in selected crops) and the expansion of land for cropping or livestock activities (Jaureguiberry et al. 2022; Balvanera et al. 2019). The second most significant direct driver in terrestrial ecosystems is direct exploitation, which includes activities such as logging, mining, fishing, hunting and wildlife trade (Jaureguiberry et al. 2022; Purvis et al. 2019).

The direct drivers provide a condensed view of how various pressures impact biodiversity across all spheres. The five main drivers are highly interconnected and often reinforce one another. For example, deforestation not only directly impacts biodiversity but also accelerates climate change. Similarly, many types of pollution, such as increasing

nitrogen surpluses, contribute to this trend. Progressing climate change also heightens the pressure from invasive species and, due to its adverse effects on crop yields, may necessitate the expansion of agricultural areas. These developments all come at the expense of biodiversity, and many are indirect. These illustrations highlight the complex mechanisms and interactions between drivers of biodiversity, which are also context-dependent, as shown by the variation in drivers across regions and realms. However, the analysis of direct drivers does not include the role of indirect drivers, for instance, how population growth and changes in consumption patterns influence each of the direct drivers. The influence of indirect drivers can hardly be quantified and ranked, given their diffuse nature and complex interaction among them (Díaz and Malhi 2022).

40.4 Conceptualizing the Interrelation Between Biodiversity and the Bioeconomy

The bioeconomy is closely connected to biodiversity, and this relationship can be both positive and negative depending on how bioeconomic activities are carried out. At its core, the bioeconomy aims to meet the growing demand for goods and services in a more sustainable way. Development strategies for the bioeconomy often emphasize using bio-based resources in ways that are not only productive but also environmentally responsible, economically viable and socially beneficial (see ▶ Chap. 2). These strategies aim to protect ecosystems and reduce biodiversity loss by minimizing harm to natural habitats.

However, increasing the use of biomass while conserving biodiversity poses significant challenges. On one hand, the bioeconomy seeks to grow and expand, which often requires higher production of renewable resources like biomass. On the other hand, this increased use of natural resources can put pressure on ecosystems and threaten biodiversity conservation (Pedersen et al. 2020). This creates a potential conflict between the goals of promoting economic growth and conserving nature.

Critics argue that the bioeconomy, when not carried out sustainably can lead to overexploitation of natural resources and contribute to land-use changes (Hall et al. 2012; see ▶ Chaps. 2 and 3), which are the two main drivers of biodiversity loss as described above. These challenges highlight the need for a balanced approach that considers both economic development and the protection and conservation of the environment to ensure a truly sustainable bioeconomy.

40.4.1 Biodiversity-Based Bioeconomies in Megabiodiverse Regions

While bioeconomy strategies can potentially aid the preservation of biodiversity, they often focus on extracting goods from nature at the expense of ecosystem integrity (Bastos Lima and Palme 2022).

In current bioeconomy strategies, there is no agreement on how and on what level biodiversity should be included (e.g. focus on genes, species, or ecosystems). Bioeconomy strategies often link ecosystem services to sustainability, but when biodiversity is valued through these services, they are defined as those meeting human needs, rather than solely for biodiversity conservation (Pedersen et al. 2020).

Especially in tropical, megabiodiverse countries, biodiversity is seen as a strategic and central resource to ensure feasible sustainable bioeconomy models (Ortega-Pacheco et al. 2018). The provision of bio-based resources and products based on but also for biodiversity is seen as key to synergistically provide "Nature contributions to people" (NCP) (Bastos Lima and Palme 2022).

Excursus 40.3 Nature's Contribution to People (NCPs)

In 2018, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has introduced a conceptual framework aimed at redefining the relationship between nature and human well-being (IPBES 2016). This framework highlights the dual dynamic of nature's provisions—referred to as "services" or "gifts" to people—and the impacts of human activities on natural systems. A key innovation within this framework is the replacement of the term "ecosystem services" with "nature's contributions to people" (NCPs). This shift emphasizes inclusivity, ensuring the framework accommodates a broader range of worldviews and cultural perspectives (Díaz et al. 2018).

In Brazil, different coalitions advocate for varying approaches to integrating biodiversity into the bioeconomy, ranging from emphasizing scientific and technological advances to prioritizing social objectives and traditional knowledge (de Queiroz-Stein et al. 2024). In countries such as Colombia, strategies aim for the use of biodiversity as a source of natural products for a more diverse resource base and territorial development (Johnson et al. 2022).

Examples include the use of biodiversity for specialty products as a strategy for the development of new bio-based value chains. This entails the sustainable use of forests (e.g. non-timber forest products value chains) as well as the integration of novel crops from plant diversity. This is the case of natural ingredients as high-added value products that are built on natural properties of bio-based resources such as plants for nutrition, medicine and cosmetics (Vargas-Carpintero et al. 2023). This view of using biodiversity can be complemented by the possibility of a restorative provision of bio-based resources. Restoring degraded areas can help to revitalize ecosystems while producing biomass (Bastos Lima and Palme 2022; de Queiroz-Stein and Siegel 2023).

These examples correspond to the "economy of biodiversity" and rely on a solid knowledge base that sustains the development of these value chains (Bastos Lima and Palme 2022; de Queiroz et al. 2024; Vargas-Carpintero et al. 2023). Given that megabiodiverse regions are also rich in traditional knowledge and societal views, the concept of a "socio-biodiverse bioeconomy" was coined (Bastos Lima and Palme 2022; de Queiroz et al. 2024; Ollinaho and Kröger 2023). This view offers a great example of the nexus not only between bioeconomy and biodiversity, but also with traditional knowledge and other forms of economic organizations and nature-humane relations (Bastos Lima and Palme 2022; de Queiroz et al. 2024). The integration of this concept in bioeconomy strategies is yet to be further discussed and operationalized, though. Exploiting specific NCP in rich biodiverse regions can be detrimental for biodiversity, when for example converting natural ecosystems into cropland or pastures for the large-scale (monoculture) production of a few commercially attractive bio-based resources (Bastos Lima and Palme 2022).

Excursus 40.4 Germany's Development Cooperation with Ecuador

The Federal Ministry for Economic Cooperation and Development (BMZ) of Germany supports Ecuador in conserving its biodiversity while promoting sustainable use to generate economic benefits. Recognizing biodiversity and protected areas as valuable economic assets, Ecuador is increasingly focusing on utilizing renewable resources through the bioeconomy to reduce dependence on fossil fuels.

BMZ helps its partners develop sustainable value chains by collaborating with the private sector and producers' associations. This includes applied research on innovative "green" products and providing funding to small and medium-sized enterprises (SMEs) in agriculture that adopt biodiversity-friendly, resource-efficient production methods. For example, GIZ (German International Cooperation Society), on behalf of BMZ, advises local producers on establishing deforestation-free cocoa production, helping foster sustainable economic development and reduce rural poverty.

40.4.2 Conceptual Framework of the Biodiversity Bioeconomy Nexus

The relationship between biodiversity and the bioeconomy is both dynamic and complex, with the potential for both synergies and trade-offs. As the bioeconomy seeks to capitalize on biological resources, it interacts with ecosystems in diverse ways. In some cases, bioeconomic practices can promote biodiversity conservation, while in others, they may exacerbate threats to ecosystems. One of many areas of tension between biodiversity and bioeconomy is conceptualized in Fig. 40.2.

Starting from the bioeconomy side, the design of the bioeconomy systems determines the potential increase or decrease of drivers of biodiversity loss, such as land-use change and overexploitation of natural resources, both biotic and abiotic.

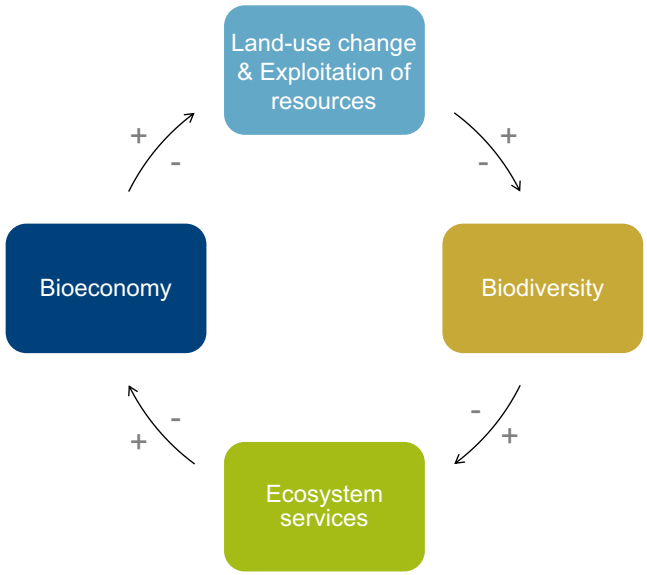


Fig. 40.2 Conceptual relationship of the bioeconomy and biodiversity, considering ecosystem services and two main drivers of biodiversity loss as exemplary areas of tension

One key aspect is the increased production and expansion of crops for material or energy production, which can lead to a significant change in rural structure, displacing other crops and thus increasing the demand for land (Searchinger et al. 2008). This often leads to intensification of land use, deforestation, and habitat destruction, all of which have negative consequences for biodiversity. As a result, the bioeconomy, in its drive for greater agricultural and forestry output, may contribute to habitat loss and fragmentation, the key direct drivers of biodiversity decline.

Starting from the biodiversity side, the abundance and quality of biodiversity determine the availability of ecosystem services for the bioeconomy. For example, a heterogenous landscape with high share of semi-natural habitat can host a high diversity of pollinator species that in turn provide pollination services to ensure consistent yields and quality for crops like rapeseed, apples and coffee (Reilly et al. 2024; Siopa et al. 2024). Declines or even a collapse in pollination services were found to result in considerable economic welfare costs, particularly on the consumer side (Feuerbacher et al. 2025; Lippert et al. 2021). Similarly, tropical forests rich in biodiversity are sources of bioactive compounds critical for developing medicines.

The bioeconomy can therefore proverbially bite the hand that feeds it. Ideally, the bioeconomy should avoid biting and rather feed the hand that feeds it, by fostering approaches that support biodiversity conservation e.g. with flowering and perennial crops or paludiculture.

40.4.3 A Normative Perspective on the Biodiversity–Bioeconomy Nexus

From a normative perspective, developing the bioeconomy should include biodiversity conservation as a key objective. This can be illustrated by two observations:

1. *Bioeconomy benefits from biodiversity due to its link to ecosystem services (see also ► Sect. 6.4 and ► Chap. 8)*
   - *Provisioning services:* Biodiversity underpins the variety and quality of goods ecosystems provide, such as biomass, the central building block of the Bioeconomy. A diverse range of crops, fish and livestock relies on genetic diversity for disease resistance, productivity and adaptation to changing environments. Wild relatives of crops often harbor genes crucial for improving agricultural varieties. Also, many medicines are derived from plants, fungi, and microorganisms, whose diversity provides a vast pool of biochemical compounds for drug development. As the bioeconomy requires freshwater, biodiverse wetlands and forest ecosystems filter and regulate freshwater supplies, maintaining water quality.

Excursus 40.5 Nagoya protocol

The "Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization (ABS) to the Convention on Biological Diversity" is an international agreement and supplement to the United Nation's Convention on Biological Diversity that provides the legal framework for the "fair and equitable sharing of benefits arising out of the utilization of genetic resources (About the Nagoya Protocol (cbd.int))". It requires that in cases where genetic resources (e.g. a plant variety or wild type) are to be utilized, a balance is to be struck between the different interests of the countries of origin of genetic resources and those countries in which the genetic resources are used. Therefore, all involved stakeholders have to ensure that they comply with the United Nation's Convention on Biological Diversity as well as the set of access, benefit-sharing and compliance obligations defined by the protocol.

More information regarding the Nagoya protocol may be found on the website of the Secretariat of the Convention on Biological Diversity.

- *Regulating services:* Biodiversity enhances ecosystems abilities in regulating natural processes. Most prominently, bioeconomy benefits from pollination, a service provided by insects and other animals. Globally, about 75% of crops are highly dependent on pollinators, which comprise about 35% of total crop production (Klein et al. 2007; IPBES 2016). Also, pest and disease control, a service that increases in diverse ecosystems is crucial for a bioeconomy as pests and diseases cause up to 40% crop loss every year globally (FAO 2022). Other regulating services that are promoted by biodiversity is climate regulation, as diverse ecosystems store and cycle carbon effectively (Mekonnen and Dejene 2018), and water regulation, a mechanism forest and wetland diversity ensure, reducing floods and maintaining base flows (CBD 2015). Both services support the basic requirements of primary production.
- *Supporting or habitat services:* Biodiversity supports the underlying ecological processes that maintain habitats and enable sustainable agricultural production. Nutrient cycling for instance, depends on microbial diversity in soils to break down organic matter and recycle nutrients (see ▶ Chap. 14). Different plant species facilitate nitrogen fixation and nutrient transfer. Microorganisms are also crucial for fertile soils (Yadav et al. 2021).
- *Cultural services:* Biodiversity enriches human experiences with nature. It comprises an indispensable educational and scientific value: Rich biodiversity offers opportunities for discovery and learning, from species behavior to potential applications in technology and medicine. This biological knowledge is another building block of the bioeconomy (see ▶ Chap. 5). Moreover, cultural identity, health and well-being constitute key aspects of human-nature relations.

2. *A sustainable bioeconomy can reduce many direct and indirect drivers of biodiversity loss and can actively support biodiversity conservation.*

Bioeconomy also presents potential for synergies, particularly through bioeconomy approaches that directly support biodiversity (Vargas-Carpintero et al. 2021). Examples include biodiversity-friendly agricultural practices, e.g. inter-cropping and agroforestry and the valorization of diverse and biodiversity-friendly wild-plant mixtures and crops (e.g. Silphie) (see ▶ Chap. 6).

While the bioeconomy is often related to land use change and resource exploitation, this relation is no prerequisite for its success. Many bioeconomy principles, such as the cascading use of biomass, actively work against wasteful resource exploitation. Also, biomass production in artificial environments, such as vertical farming or algae production, require less land (Kobayashi et al. 2022) (see ▶ Chaps. 7 and 10).

To further ease the pressure on land, a shift of consumption pattern towards a diet that is lower in animal products and higher in plants is frequently advocated, as animal products require more land compared to plants (Agora Agriculture 2024).

Bio-based products commonly have a lower carbon footprint than their fossil substitutes, mitigating climate change, another important driver of biodiversity loss (Brandão 2020). Also, bioeconomy principles, such as circularity can reduce pollution, for instance related to nitrogen use (see ▶ Chap. 3). By reducing dependence on non-bio-based materials, such as fossil fuels and minerals, the bioeconomy can lower the exploitation of natural resources and the associated environmental degradation, including reduced mining and pollution. These shifts may help alleviate pressures on ecosystems, reducing the impacts of climate change and pollution.

As illustrated in this section, bioeconomy offers both challenges and opportunities for biodiversity conservation. When shaping the transition to a sustainable, bio-based economy, both should be accounted for (Pedersen et al. 2020).

Increasing pressure on known drivers for biodiversity loss, such as land use change should be avoided at any cost. Without careful planning and management, the drive to expand the bioeconomy could result in harmful trade-offs, such as habitat destruction, overexploitation of natural resources and the degradation of ecosystems. Balancing these competing priorities will be key to ensuring that the bioeconomy contributes positively to both human well-being and the preservation of biodiversity (Pedersen et al. 2020).

Synergies should be facilitated by adopting sustainable practices that align economic goals with ecological principles, such as promoting diverse, resilient ecosystems in forestry, implementing biodiversity-friendly agricultural techniques and developing environmentally safe biofuel and aquaculture production methods.

To consider both challenges and opportunities, the bioeconomy transition necessitates inclusive governance and political dialogue to ensure sustainable development (de Queiroz-Stein et al. 2024; Bastos Lima and Palme 2022). Long-term sustainable management is required to safeguard biodiversity in well-functioning and resilient ecosystems.

Questions

1. What is biodiversity, and what are some key metrics used to measure it?
2. How is the bioeconomy dependent on biodiversity, and what are the main drivers of biodiversity decline?
3. How do synergies and trade-offs influence the relationship between biodiversity and the bioeconomy?

Answers

1. Biodiversity refers to the variety and variability of life on Earth, including species diversity, genetic diversity, and ecosystem diversity. Key metrics to measure biodiversity include species richness (the number of different species in a given area), species evenness (the relative abundance of species), and indicators like the Shannon Index or Simpson's Diversity Index.
2. The bioeconomy relies on biodiversity for resources like plants, animals, and microorganisms that provide raw materials and ecosystem services essential for sustainable production. Key drivers of biodiversity decline include habitat loss, pollution, overexploitation of resources, climate change and invasive species. These pressures threaten the natural systems that the bioeconomy depends on.
3. Synergies occur when biodiversity and the bioeconomy reinforce each other, such as using sustainable agricultural practices that preserve ecosystem services while enhancing productivity. For instance, agroforestry systems support diverse species, improve soil health, and provide economic benefits like timber and crops. Conversely, trade-offs arise when prioritizing economic goals harm biodiversity, as in large-scale monoculture farming, which boosts short-term yields but reduces habitat diversity and ecosystem resilience. Striking a balance requires holistic approaches like circular economy models, which minimize waste and resource use, or policies incentivizing practices that maintain biodiversity. Recognizing synergies helps align conservation with economic goals, while managing trade-offs is key to ensuring long-term sustainability in the bioeconomy.

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Sustainability Assessment

Jan Weik, Valentin Schlecht, Nirvana A. Marting Vidaurre, Jan Lask, and Moritz Wagner

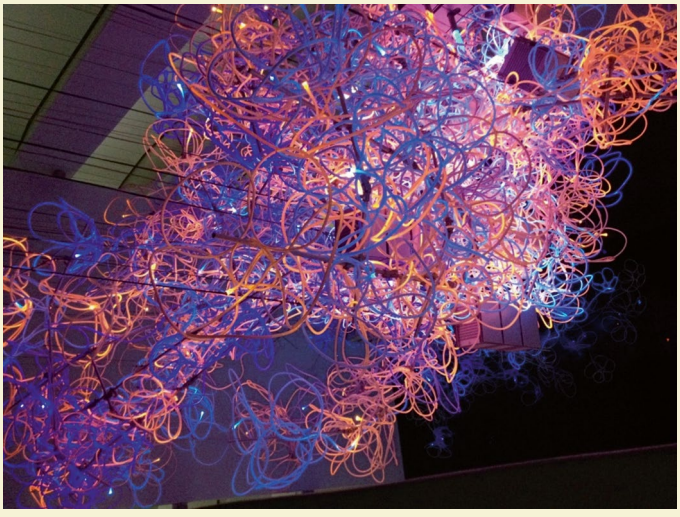


Fig. 41.0 Sustainability assessment. © Ulrich Schmidt (► https://doi.org/10.1007/000-hvp)

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Earlier in this book, sustainability was introduced as a key principle of the bioeconomy. While *bioeconomy systems are not sustainable per se*, science-based assessment methods are required to address this principle in both novel and traditional bioeconomy systems. This chapter provides an overview of sustainability assessment methods that support the evaluation of products, services, systems and organisations within the bioeconomy. The chapter begins with a brief refresher on the concepts of sustainability and explains the relevance of sustainability assessment. It then characterises sustainability assessment methods, followed by an introduction to sustainability indicators as a means of quantifying different sustainability aspects. This brief overview is followed by dedicated sections on environmental, social and economic assessment methods with a focus on Life Cycle Assessments, Social Life Cycle Assessment and Life Cycle Costing. The concepts of end-point results, multi-criteria decision analysis and true cost accounting are also introduced, particularly in the context of improved communication. The final part of the chapter is dedicated to the use of sustainability assessment in the bioeconomy. Areas of application are described, and the challenges associated with the assessment of agricultural systems, novel technologies and regional specificities are highlighted.

Learning Objectives

After studying this chapter, you will…

- …be able to classify different types of sustainability assessment methods and sustainability indicators (see ► Sect. 41.1).
- …be able to explain the basic procedure of life cycle assessment, social life cycle assessment and life cycle costing (see ► Sects. 41.2.1, 41.3.1 and 41.4.1).
- …be able to describe methods that support the communicability of quantitative sustainability information (see ► Sect. 41.5).
- …be able to explain the characteristics of sustainability assessment in the field of the bioeconomy (see ► Sect. 41.6).

41.1 From the Concept of Sustainability to the Assessment of Sustainability

Sustainability is a key principle of the bioeconomy (see ► Sect. 3.1). It refers to an economy that meets the needs of the present society, without compromising the ability of future generations to meet their own needs (Brundtland 1987). The concept includes an environmental, social and economic dimension, embracing the multifunctionality of bioeconomy systems (Barbier 1987; Purvis et al. 2019). Sustainability can also be defined as "weak" or "strong" depending on the extent to which natural capital can be substituted by manufactured capital (Turner 1993). While these meta-level concepts of sustainability were explained in ► Chap. 3, the question is raised how the bioeconomy can become more sustainable in practice (see examples for agriculture in ► Chap. 31 and for business in ► Chap. 35). An important piece in this puzzle – sustainability assessment – is addressed in this chapter.

What Is Sustainability Assessment?

Sustainability assessment is a process that guides decision-makers towards sustainability. The process consists of two parts: The contextual part includes a problem statement and ensures the interaction with the social and political environment. The assessment part applies context-specific sustainability assessment methods to operationalise the sustainability performance of the assessed system using sustainability indicators. The assessed system can be, for example, a product, service, value chain, region or organisation. The assessment methods generate sustainability information, including environmental, social and economic indicator results but also further information related to gover-

nance or product quality. Sustainability assessment is ideally conducted ex-ante, during the design or development phase. Common goals are the comparison of alternatives, the detection of sustainability hot spots for optimisation and the identification of sustainability trade-offs. Common fields of application are policy development, process optimisation and product design (Ochsenbein et al. 2004; Hacking and Guthrie 2008; Binder et al. 2020; Bond et al. 2012; Sala et al. 2015).

Why Is Sustainability Assessment Relevant?

Sustainability assessment is essential for responsible decision-making, providing a structured approach to evaluating the environmental, social and economic impacts of actions. It supports process optimisation, policy development and corporate sustainability by ensuring that decisions are both effective and aligned with broader sustainability goals (Bond et al. 2012). It minimises risk by identifying potential adverse impacts early, enabling proactive solutions to avoid environmental damage, social injustice and financial loss. By ensuring compliance with legal and regulatory standards, it helps organisations meet their obligations while promoting sustainable practices. In addition, it can enhance corporate reputation by demonstrating a commitment to sustainable development (Hahn 2022).

How Is Sustainability Assessment Conducted?

The basis for a sustainability assessment is a conceptual framework. A general structure proposed by Halla and Binder (2020) distinguishes two main parts: the contextualisation of the assessment, and the assessment process itself. The assessment process always takes place in the context of the assessment and cannot take place in isolation from it. The two parts are further specified in six steps (Fig. 41.1).

The first part sets the stage and contextualises the stated problem. This involves three steps (Halla and Binder 2020):

1. Understanding sustainability: Among the various concepts and definitions of sustainability (see ▶ Sect. 3.1), a common understanding of the term is established among stakeholders, including sustainability goals and criteria.
2. Societal processes: This part specifies the purpose and expected outcome (impact) of the work in relation to the various stakeholders associated with the assessed system.

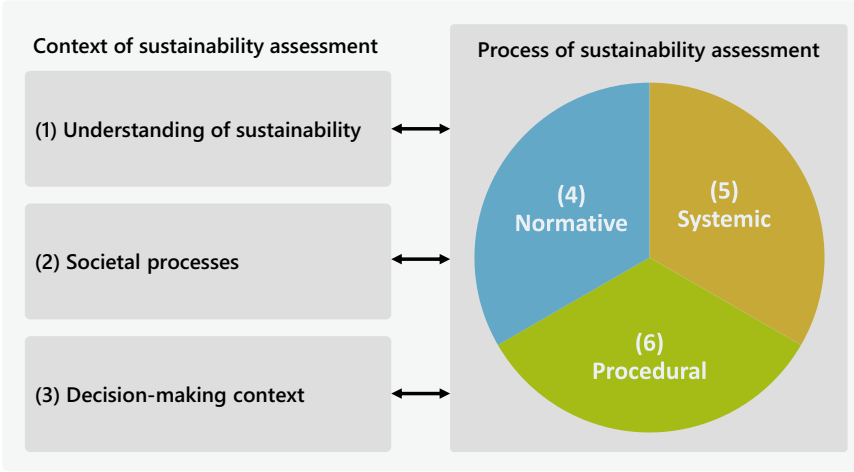


Fig. 41.1 Key components of a conceptual framework for sustainability assessment. (Adapted from Halla and Binder 2020)

3. Decision-making context: The decision context includes a clear definition of the assessed system and the scope of the assessment. A stakeholder analysis is also carried out, and the commissioners of the assessment are assigned. Decision-making rules are established, e.g. for handling trade-offs or weighting indicator results.

   The now given context determines the design of the assessment process, such as the choice of methods and indicators or the number and type of stakeholders involved. This is described in the second part, the assessment process. It includes a normative, a systemic and a procedural process (Binder et al. 2010; Halla and Binder 2020):
4. Normative process: Based on the understanding of sustainability and general goals defined in the first part, more specific goals are defined. For conflicting goals, the defined trade-off rules or weightings are applied. This step also includes the establishment of normative statements based on the indicator results and decision-making rules.
5. Systemic process: Description of the assessed system (as simple as possible, as complex as necessary) and selection of indicators that represent all relevant sustainability aspects. Methods of sustainability assessment are selected accordingly.
6. Procedural process: This includes the steps taken to generate indicator results, such as data collection and calculation procedures. These steps are accompanied by the participation of stakeholders who provide data or evaluate the generated results. The final steps include the dissemination of the generated results and recommendations.

Note that the six steps are not strictly sequential. Sustainability assessments usually follow an iterative approach that allows for adjustments during the assessment process (e.g. ISO 2006a, b). The arrows in ◘ Fig. 41.1 underline the mutual interaction between the contextualisation part and the assessment part.

41.1.1 Characterisation of Sustainability Assessment Methods

The choice of sustainability assessment method depends on the context defined in the first part of the conceptual framework described in ◘ Fig. 41.1. There are various methods available for sustainability assessment. A selection is given in ◘ Table 41.1. All of these methods have distinct characteristics and fields of application:

- **Qualitative vs. quantitative:** Most methods are quantitative assessment methods, e.g. product carbon footprints. Qualitative assessment methods include certification schemes (see ▶ Sect. 31.2) or management systems.
- **Sustainability dimension:** There are distinct methods for environmental, social and economic assessment (e.g. life cycle assessment, social life cycle assessment and life cycle costing) and methods that cover more than one dimension (e.g. life cycle sustainability assessment (LCSA), a combination of the before mentioned, see ▶ Excursus 41.2).
- **Entity of concern:** Some methods have been developed specifically for the assessment of products and services (e.g. life cycle assessment), while others are designed for organisations (e.g. corporate carbon footprint) or whole systems, such as the assessment of regions or countries (e.g. environmentally extended multi-regional input–output models (EEMRIO)).
- **Life cycle perspective vs. single stage perspective:** "Life cycle methods", such as life cycle assessment, consider the entire life cycle of a product, from cradle-to-grave, including raw material extraction, manufacturing, distribution, use phase and end-of-life (see ▶ Excursus 41.1). Other sustainability assessment methods focus on a specific life cycle stage, e.g. corporate footprints.

Table 41.1 Characterisation of selected sustainability assessment methods

	Data type	Dimension	Entity of concern	Perspective	Approach	Number of indicators
Organic farming certification	Qualitative	Environmental, Social	Products, farms	Single stage	Bottom up	Many
Sustainability management system	Qualitative	Environmental, social, economic	Organisations	Single stage	Bottom-up	Many
Corporate carbon footprint	Quantitative	Environmental	Organisation	Single stage (Scope I&II)	Bottom-Up	One
Life cycle sustainability assessment	Quantitative	Environmental, social, economic	Products	Life cycle	Bottom up or top down	many
Social impact assessment	Qualitative and Quantitative	Social	Products, services, System	Single stage	Bottom up	many
Input-/ Output-assessment	Quantitative	Economic, environmental, social	Product groups, services, economies	Life cycle	Top down	few
Investment appraisal	Quantitative	Economic	Products, services	Single-stage or life cycle	Bottom up	few
True cost accounting	Quantitative	Environmental, social, economic	Products, services, System	Life cycle	Bottom up or top down	Many, but one aggregated (cost)

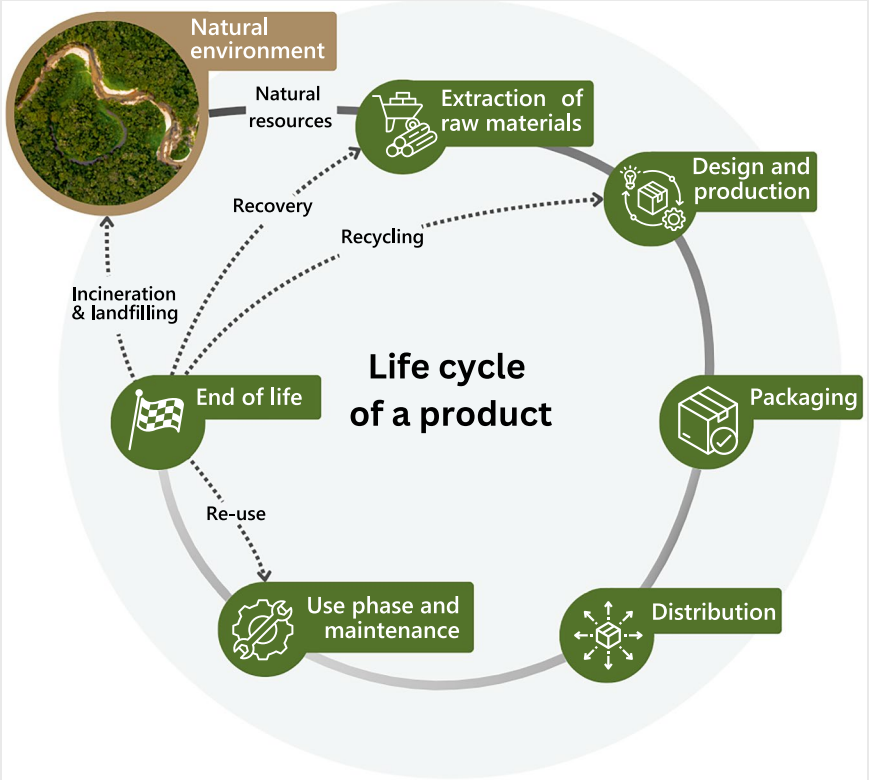
- **Bottom-up vs. top-down:** Bottom-up methods model the assessed system, e.g. a product system or value chains from scratch using parameters provided by primary producers (e.g. process-based life cycle assessment). Top-down methods (e.g. EEMIRO) use macroeconomic statistics to model the assessed system such as economies, industries and product categories. Bottom-up methods focus on the granularity of the assessed system, while top-down methods take a broader perspective and embed the assessed system into a larger system.
- **Single indicator vs. multi-indicator methods:** Footprint methods, such as water or carbon footprints, focus on a single indicator. While carbon footprints are very popular, conclusions about the sustainability performance of an assessed system cannot be drawn from a single indicator. Multi-indicator methods, such as multi-criteria decision analysis (MCDA), are recommended for the generation of comprehensive sustainability information.
- **Footprint vs. handprint:** Most sustainability assessment methods focus on the negative impacts of the assessed system, such as the carbon footprint of a company that pays into the anthropogenic greenhouse effect and accelerates climate change. In contrast,

the sustainability handprint shows the benefits of the assessed system. For instance, the renaturation of peatland in the long run avoids further greenhouse gas emissions from that land and may increase biodiversity. Some methods can include both impacts and benefits, such as the avoided burden concept in consequential LCA or ecosystem service valuation in true cost accounting (see ▶ Sect. 41.5.3).

Excursus 41.1. Life cycle thinking

Systems thinking is a key principle of the bioeconomy (see ▶ Sect. 3.5). An important concept in this context is *Life Cycle Thinking* (LCT). LCT expands beyond focusing solely on one production stage (e.g. manufacturing) by examining the full environmental, social and economic impacts of a product throughout its entire life cycle, from cradle to grave. This includes the extraction of raw materials, design and production, packaging and distribution, use and maintenance, as well as several end-of-life options (◘ Fig. 41.2). The primary goals of LCT are to minimise resource use, reduce emissions and enhance socio-economic outcomes across a product's lifespan, promoting connections between economic, social and environmental factors within an organisation and its supply chain. LCT can also avoid *burden-shifting* where the sustainability improvement at one stage has adverse effects on another stage. For instance, while electric cars reduce direct combustion emissions during the use phase, the emissions are shifted to the electricity production stage.

Do you want to learn more about life cycle thinking? Take a look at ◘ Supplementary Material 41.1, a video from our MOOC "Concepts of Sustainable Bioeconomy" (2021).



◘ **Fig. 41.2** Life cycle thinking concept applied to the life cycle of a product. (Adapted from UNEP/SETAC 2023)

41.1.2 Characterisation of Sustainability Indicators

Most sustainability assessment methods have in common that they use sustainability indicators to operationalise sustainability[1] (Hartmuth et al. 2008). The choice of sustainability indicators is part of the conceptual framework development. Indicators relevant for the assessed system are identified by means of a materiality analysis, a method that helps to identify relevant sustainability aspects and related indicators (Beske et al. 2020; SBTN 2024).

> Indicator is Latin for "one who points out". ***Sustainability indicators*** thus point out the status of sustainability aspects related to the assessed system.

For instance, greenhouse gas emissions are an indicator for climate change, as there is a causal relation between them (see ▶ Sect. 1.1).

There are plenty of sustainability aspects and related indicators with specific characteristics. In the following, these characteristics are explained by the example of a crop production system:

- **Qualitative vs. quantitative:** Qualitative indicators in agriculture reflect a certain practice. An example would be "soil improvement practice". For instance, in terms of soil conservation, it makes a difference if the farmer uses a plough or a cultivator. A plough turns the soil and disturbs the soil structure and fauna. A cultivator, on the other hand, is gentler. However, the practice-based indicator only shows that there is a difference not the magnitude of the difference. Here, one or several quantitative indicators are needed, which show the performance of the chosen practice, such as "soil organic content" (FAO 2013).
- **Regional vs. global:** Crop production has both local, as well as global implications. The use of mineral fertiliser causes nitrous oxide (N_2O) emissions that lead to global warming, an effect that is visible all around the world. "Climate change" is, therefore, an indicator that points out a global issue. Leakage of nitrogen fertiliser as nitrate can cause nutrient oversupply in water bodies, resulting in eutrophication (Learn in ▶ this video what eutrophication is). While these nutrients are transported in water bodies to some extent, eutrophication is a rather regional effect (Sutton et al. 2011).
- **Cause vs. effect:** The use of nitrogen fertilisers has an effect on climate change. The reason is that a share of the nitrogen is converted into nitrous oxide (N_2O), a very potent greenhouse gas. The indicator "N_2O emissions" is a cause-related indicator. It indicates that there is N_2O released into air but not how this release affects climate change. The effect of N_2O is shown by an indicator that includes N_2O's effect on earth's radiative forcing (Watch ▶ this video and learn "How Do Greenhouse Gases Actually Work?"). For instance, carbon footprint methods use this effect-related indicator to identify the magnitude of certain greenhouse gas emissions. This classification is closely related to the Pressure-State-Response (PSR) framework. Pressure indicators point out causes for e.g. environmental pollution such as greenhouse gas emissions. State indicators show the condition or quality of the environment or its components as a result of pressures, e.g. greenhouse gas concentration in the atmosphere. Response indicators reflect societal actions to address e.g. environmental problems or improve environmental conditions, such as the amount of a carbon tax (OECD 1993).
- **DPSIR:** The DPSIR framework is a further development of the PSR framework with the indicator categories diver, pres-

1 Operationalisation of sustainability means that the concept of sustainability becomes measurable by using indicators. In the business context, the term operationalisation is sometimes also used synonym to "to put something into practice".

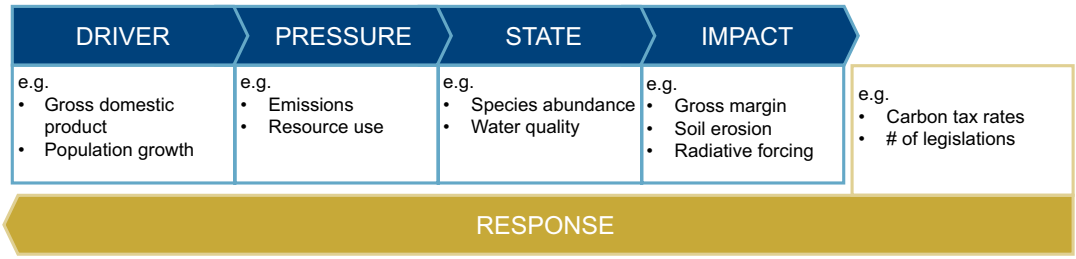


Fig. 41.3 Indicator classification according to the driver–pressure–state-impact–response (DPSIR) approach

sure, state, impact and response (Fig. 41.3) (Smeets and Weterings 1999).

- **Midpoint vs. endpoint:** In LCA, most indicator frameworks include midpoint categories, while some also include endpoint indicators. This distinction is related to the related impact pathway and to where the indicator is located closer to the origin of impact (mid-point) or to the area of protection (endpoint) (see ▶ Sect. 41.5.1) (Rosenbaum et al. 2018).

Many sustainability indicator frameworks exist. A general and very comprehensive selection provides the SDG framework (see ▶ Sect. 2.3.4) with 231 unique indicators related to 169 sub-targets of 17 sustainable development goals (UN 2017). For the agricultural context, there is, for instance, the SAFA (Sustainability Assessment of Food and Agriculture Systems) framework (see ▶ Sect. 31.2, Fig. 31.2). It includes 116 indicators, structured around four sustainability dimensions: Good Governance, Environmental Integrity, Economic Resilience and Social Well-being (FAO 2013). The Response-Inducing Sustainability Evaluation (RISE) framework, a tool for assessing the sustainability of farms, comprises 50 indicators (BFH-HAFL 2022). Method-specific indicator frameworks are available, for instance, for LCA, e.g. ReCiPe2016 with 18 environmental impact categories with respective midpoint impact indicators and 3 areas of protection with respective endpoint indicators (Huijbregts et al. 2017). For social LCA, the UNEP framework provides six stakeholder groups, 5–11 subcategories for each stakeholder and various indicator suggestions for each subcategory (UNEP 2021a, b). A more comprehensive overview on indicator frameworks is available in Supplementary Material 41.2.

41.2 Environmental Assessment Methods

Environmental sustainability assessment is a crucial process for evaluating the impact of human activities on the environment and guiding decision-making towards more sustainable practices.

Three key approaches used in this field are environmental impact assessment, process-based Life Cycle Assessment (LCA) and input–output-based LCA (I/O LCA). Each of these will be briefly introduced in the following:

- ***Environmental impact assessment*** is used to analyse and evaluate potential risks to environmental hazards and/or human health associated with a particular activity. This could include policies as well as more specific, focused activities such as construction projects for which the likelihood and severity of potential adverse effects are evaluated. Typically, these assessments are focused on local/direct effects of the activity (i.e. neglecting effects in supply chains). For instance, an environmental risk assessment could be required when planning a new biorefinery in order to assess the potential impact of noise due to construction and operation on bird populations in its immediate surroundings. Thereby, this approach helps decision-makers understand and manage potential environmental risks, allowing for more informed choices in project planning (DG Environment n.d.).

- ***Process-based Life Cycle Assessment*** (LCA) is a method that enables comprehensive evaluation of the environmental impacts of a product (or service) throughout its entire life cycle, thus including also indirect impacts (e.g. from the supply chain). The most widely considered environmental impact is climate change. If an LCA is prepared only with regard to climate change, the LCA is referred to as (Product) Carbon Footprint. For any LCA, resource use and emissions at each stage of the product's life cycle are accounted for—from raw material extraction, via product use to final disposal. Using environmental models, this information is then used to quantify the potential environmental impacts. A special characteristic of process-based LCA is that they rely on detailed insights into the processes that are making up a product's life cycle (Bjørn et al. 2018). As such, LCAs can be a valuable tool for product development and improvement.
- ***Input-output-based LCA*** (I-/O-LCA) or multiregional input–output analysis (MRIO) is an alternative approach to process-based LCA, which also captures indirect impacts. It uses economic data on production, demand, in- and exports of countries and sectors. The underlying input–output tables provide a historical data source of global material and trade flows, as well as production and consumption recipes of past years. The methods of input-output analysis were developed by Leontief (1986). With the Leontief calculus, we can investigate the amount of a primary resource needed throughout the economy to meet consumer demand for a product in monetary (and physical) units. When linked to environmental impacts, this technique can be used to measure ecological impacts associated with producing one euro of a good in a given year. As such it allows for analysis of large-scale systems and organisations as well as entire economies (Mattila 2018).

Each of these methods offers unique insights into environmental sustainability. By employing these tools, researchers, policymakers and businesses can make more informed decisions to promote environmental sustainability and mitigate negative impacts on our planet.

41.2.1 Spotlight: Life Cycle Assessment

Life Cycle Assessment (LCA) is a systematic method used to evaluate the environmental impacts of a product, process or service throughout its entire life cycle (ISO 2006a). As such LCA is a practical application of life cycle thinking (see ► Excursus 41.1) and encourages decision-makers to look beyond the immediate effects and consider upstream and downstream consequences. Typically, this happens also for multiple environmental issues at once, for instance climate change, acidification, eutrophication and others, offering a broad perspective on environmental performance and helping to prevent environmental *trade-offs*.

It is important to note here that LCA, in its current practical application, has a limitation: while it allows practitioners to identify environmental hot spots, optimise processes and compare products, it does not indicate whether a product or project is genuinely sustainable from an environmental perspective.

A ***trade-off*** describes a negative correlation. It is a situation in which the methods of achieving two goals are opposed to each other, and a balance has to be struck between them. An example of an environmental trade-off can be seen in the production of bioethanol and its subsequent use in a combustion engine. The use of bioethanol in place of fossil fuels makes a positive contribution to GHG emission reduction and thus to climate change mitigation. However, at the same time, the cultivation of the feedstock for bioethanol production, in particular the application of nitrogen fertiliser, has a negative impact in the category eutrophication.

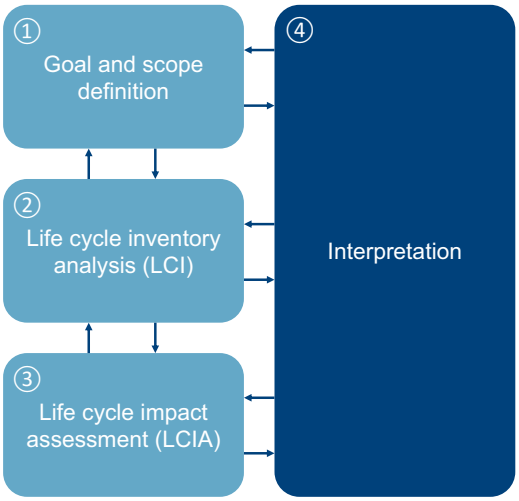


Fig. 41.4 Life cycle assessment framework according to ISO 14040. (Based on ISO 2006a)

Per principle, LCA gives preference to science-based approaches and aims for transparency in regard to methodology, data sources and assumptions, enabling reproducibility of the results. In addition, LCA is intentionally defined as an iterative approach, allowing for refinement and improvement of data and assumptions as the study progresses.

Implementing these principles, LCA is guided by international standards, most importantly ISO 14040 and ISO 14044, which provide a framework for conducting LCA studies (ISO 2006a, b). These standards define a procedure made up of four phases (Fig. 41.4): (1) Definition of goal and scope, (2) Life cycle inventory (LCI) analysis, (3) Life cycle impact assessment (LCIA) and (4) Interpretation.

In the following, each of these phases will be quickly introduced, highlighting the most important aspects.

1. **Definition of Goal & Scope**

   In the first phase of an LCA study, objectives and defining parameters are defined.

   The objectives of an LCA can be manifold and include, among others:

- The assessment and quantification of the potential environmental impact of a product or service for one or more environmental issues,
- The identification of environmental hot spots in a production process,
- The quantification of environmental trade-offs,
- The provision of decision support for the environmental improvement of a production process or unit,
- The development of a database for customer information and "green" marketing strategies.

Depending on the selected objective(s), further parameters need to be defined accordingly. This includes, for instance, the selection of the study's functional unit and the corresponding reference flows.

> According to ISO 14040, the ***functional unit*** (FU) is the "quantified performance of a product system for use as a reference unit" (ISO 2006a, p. 10). The results of all impact categories can be related to this reference unit. In the case of energy-producing systems, such as bioethanol production, it could be, for example, 1 GJ. This enables a comparison with other bioenergy sources or with a fossil reference. The ***reference flow*** is the output from processes in a given product system that is necessary to fulfil the function expressed by the FU. So, with a FU of, for example, 1 GJ, the reference flow (e.g. in litres) is higher for bioethanol than for fossil gasoline, because the energy content of bioethanol is lower.

Also depending on the selected objectives, *system boundaries* need to be defined accordingly. These define which activities are included in the assessment and what is excluded from the assessment. Based on the life cycle perspective, typically, two approaches are distinguished:

If the system boundaries include all processes from raw material extraction and manufacturing but also the product's use phase and disposal, this is typically referred to

as *cradle-to-grave* analysis. In comparison, it is also possible to perform a so-called *cradle-to-gate* analysis, limiting the boundary to the production process.

▶ System Boundary of Miscanthus Cultivation

In the following, the life cycle of miscanthus (Lewandowski et al. 2016) is used as an example to give a first impression of a cradle-to-gate analysis. The product system includes all steps related to the cultivation of miscanthus. The steps "Fertilization" and "Harvest" are repeated 20 times as miscanthus is a perennial crop that is cultivated over a period of 20 years. Arrows represent product flows, such as inputs (e.g. "Fertiliser") and outputs (e.g. "Biomass as Bale"). As such, the cradle-to-gate analysis includes all unit processes related to the biomass cultivation process up to the farm gate, including crop production, harvest and transport from field to farm (Fig. 41.5). ◀

2. **Life Cycle Inventory Analysis**

After defining the goal and scope of the study, an inventory of all flows related to the product system is compiled. This includes material input and outputs of the system as well as environmental exchanges such as emissions associated with each stage of the life cycle (ISO 2006a).

This stage is typically supported by LCI databases, such as ecoinvent, which provide datasets for different background processes, for instance, electricity production (Wernet et al. 2016).

3. **Life Cycle Impact Assessment**

Life Cycle Impact Assessment (LCIA) is the third phase of an LCA study. It follows the life cycle inventory (LCI) collection, where all relevant flows that occur in relation to a product's life cycle are collected. For instance, in an assessment of heat generation from wood, all the resource use and all the emissions that occurred during the provision of wood, as well as its

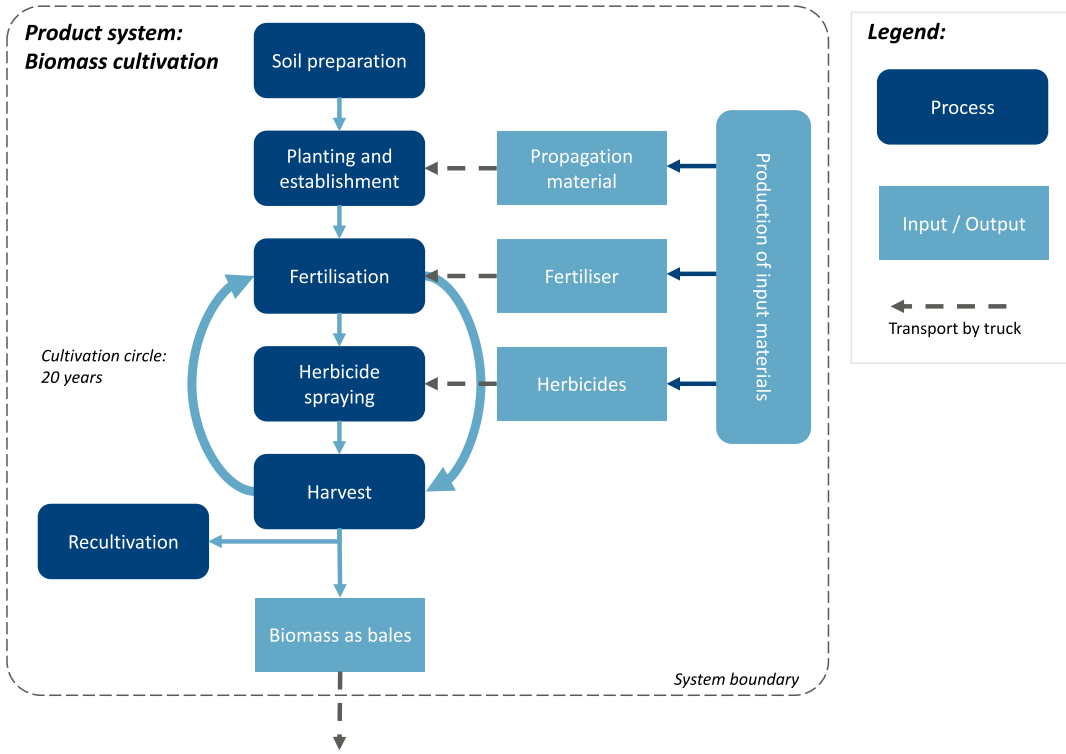


Fig. 41.5 Product system with cradle-to-gate system boundaries for miscanthus biomass cultivation. (Based on Kiesel et al. 2017)

combustion, are aggregated. For an assessment of the potential climate change impact, this means, for instance, that all the emissions of greenhouse gases such as carbon dioxide and methane are compiled in this phase (ISO 2006a).

LCIA translates the inventory data collected during the LCI phase into meaningful environmental impact indicators. This is important as the information gathered during the LCI phase does not hold information about the potential impact and as such would be challenging to interpret. For instance, 1 kg of methane emitted to the air does not have the same climate change impact as 1 kg of carbon dioxide emitted to air. Methane's global warming potential is about 30 times that of carbon dioxide (IPCC 2021).

Besides climate change, there is a large set of other environmental indicators covering many environmental aspects related to human activities. This includes, for instance, ozone depletion, acidification, eutrophication, human toxicity, ecotoxicity, resource depletion, land use and many others (Huijbregts et al. 2017). The set of environmental indicators is defined within the goal and scope phase of the LCA.

4. **Interpretation**

   The final phase involves interpreting the results to make informed decisions, identify areas for improvement and communicate findings to stakeholders. It includes different methods that support the interpretation, such as contribution analysis, uncertainty analysis and sensitivity analysis (ISO 2006a).

LCA in Practice

The practical performance of an LCA study can be supported by calculation programs, such as MS Excel, or professional LCA programs, such as LCA for Experts (previously GaBi), SimaPro and Umberto. Examples of open-access LCA software with features comparable to those of professional programs are ▶ openLCA and ▶ Brightway. The major benefit of using LCA programs is that they offer structured data processing and performance of the impact assessment calculation procedure. Users can create product systems, add collected data for the foreground system and link those to the datasets of a background database. An overview of available commercial and open-access databases can be found ▶ here.

Excursus 41.2 Life Cycle Sustainability Assessment

Life cycle sustainability assessment (LCSA) is an integrated framework that expands the Life Cycle Assessment (LCA) approach to encompass not only environmental impacts but also economic and social dimensions of sustainability. By doing so, LCSA offers a holistic perspective on the sustainability performance of products, processes, or systems across their entire life cycle—from raw material extraction to end-of-life disposal or recycling.

The environmental dimension in LCSA is covered with Life Cycle Assessment (LCA), focusing on quantifying environmental impacts. Social Life Cycle Assessment (S-LCA) evaluates social impacts, such as labour rights, community well-being and human health, influenced by the product or system over its life span (see ▶ Sect. 41.3.1). Life Cycle Costing (LCC) examines the economic aspects, including direct and indirect costs incurred throughout the life cycle (see ▶ Sect. 41.4.1).

Do you want to learn more about LCSA? Take a look at ◘ Supplementary Materials 41.3 and 41.4, two videos from our MOOC "Concepts of Sustainable Bioeconomy" (2021).

41.3 Social Assessment Methods

Economic activities affect people's lives in many ways and affect their well-being. By assessing how and in what ways people are affected by economic activities, we can identify hot spots and take action to improve their living and working conditions. Social impact assessments aim to operationalise these social impacts. They can be carried out at three different levels: Social assessment of a project or intervention, social assessment of a product or production process or social assessment of a company or organisation (Benoît Norris et al. 2020).

■ Social Assessment of a Project

One of the methodologies used to conduct a social assessment of a project or intervention is social impact assessment (SIA). This methodology aims to identify and manage social issues with the participation of affected stakeholders (ideally) from project conception to post-closure (Vanclay et al. 2015). The SIA methodology is iterative and consists of first studying the affected community and identifying its characteristics, known as community profiling. This step is followed by the identification of areas of concern. The next steps are to select indicators, establish a baseline and forecast the impact of the project on the communities. Finally, an action plan is developed that includes mitigation and enhancement strategies (Esteves et al. 2017). Two types of social impacts are recognised in SIA. These are first-order and second-order impacts. The first order or direct impacts are social changes caused by the project, while the second order or indirect impacts are those changes that occur because of a change caused by the project (Vanclay et al. 2015). The framework that accompanies this methodology is called the social framework (Smyth and Vanclay 2017). This conceptual model covers different aspects in which people are affected by projects and which contribute to human well-being. These aspects are the environment, people, community, livelihoods, culture, infrastructure, housing and land (Smyth and Vanclay 2017).

■ Social Assessment of a Product or Production Process

One method for evaluating production processes and products is Social Life Cycle Assessment (S-LCA). S-LCA aims to assess the impacts or potential social impacts on stakeholders affected by the activities carried out to produce a product, covering the entire value chain from raw material extraction to final disposal (Benoît Norris et al. 2020). As in environmental LCA, S-LCA distinguishes between two systems: foreground and background systems. The former includes the core processes that are analysed. The background system includes processes that provide the inputs required by the foreground system. As today's value chains are international, S-LCAs often require data on social aspects from different countries. This broad coverage makes the assessment of the background system challenging in terms of data. For this reason, it makes sense to collect primary data for the assessment of the foreground system, while the assessment of the background system can benefit from secondary data collected periodically and publicly available by organisations such as the International Labour Organisation (ILO). The phases followed in the S-LCA methodology are similar to those in environmental LCA. These are goal and scope definition, life cycle inventory, life cycle assessment and interpretation. The Guidelines for Social Life Cycle Assessment of Products and Organisations (Benoît Norris et al. 2020) and the Methodological sheets for subcategories in Social Life Cycle Assessment (UNEP 2021a, b) provide a list of stakeholders and impact subcategories per stakeholder that practitioners can include in their assessments. In bioeconomy, the assessment of the smallholder and family farm stakeholder is often relevant, as forestry and agriculture provide raw materials for multiple value chains (Marting Vidaurre et al. 2020).

■ Social Assessment of a Company or Organisation

It aims to assess the social impacts of organisations. An example of this type of assessment is Social Organisational Life Cycle

Assessment (SO-LCA) and Human Rights Due Diligence. There are several sustainability standards for companies that address social issues, to name a few: AA1000, SA8000, Global Reporting Initiative (GRI), ISO 26000.

41.3.1 Spotlight: Social Life Cycle Assessment

There are two types of impact assessment in S-LCA: Reference Scale (Type I) and Impact Pathway (or Type II). These methods determine how the calculations are carried out.

Reference scale impact assessment is used to assess the social performance or social risk of a product or process (Benoît Norris et al. 2020). For each of the indicators considered in the assessment, a reference scale is established, and indicator scores are assessed against it to determine the risk level of the indicator. SHDB (Benoît Norris et al. 2012), PSILCA (Loubert et al. 2023) and soca (Hamed and Ciroth 2024) are the three databases available for carrying out an S-LCA using the reference scale approach. SHDB is based on the GTAP Input–Output Database, which covers about 13,000 sectors in 244 countries (Benoît Norris et al. 2020). PSILCA is based on the EORA input–output database. It covers more than 14,800 sectors in a total of 189 countries (Loubert et al. 2023). The soca database is the result of mapping the social indicators and data from PSILCA to ecoinvent. It allows to perform simultaneously an S-LCA, an LCC and an environmental LCA but is limited to the ecoinvent country resolution. These three databases allow the use of an activity variable to calculate the social risks associated with a value chain. An activity variable in S-LCA is a measure of the process activity related to the process output (Benoît Norris et al. 2020). Worker hours and value added are commonly used activity variables. For example, worker hours for each of the processes within the system boundaries provide information about the share of those processes in the whole system. In addition, because they relate to the workplace, worker hours can be used to assess indicators of working conditions. This can be achieved by weighting the worker hours with the risk level associated with the social indicator. Figure 41.6 shows a simple example of an S-LCA following the reference scale approach, also called social risk assessment. In the example, biomass cultivation and conversion

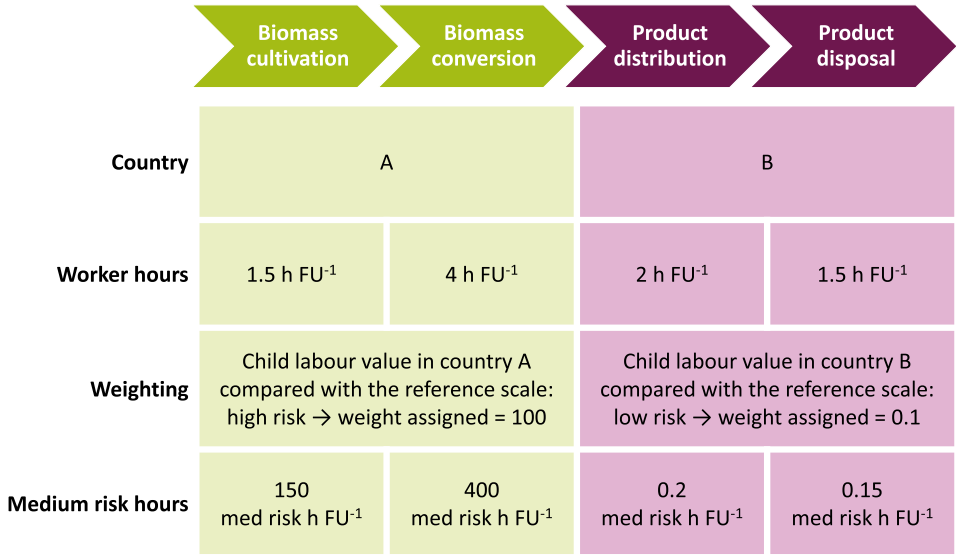


Fig. 41.6 Example of social risk assessment using the reference scale approach, showing a bio-based value chain spanning two countries with different risk scores for the child labour indicator

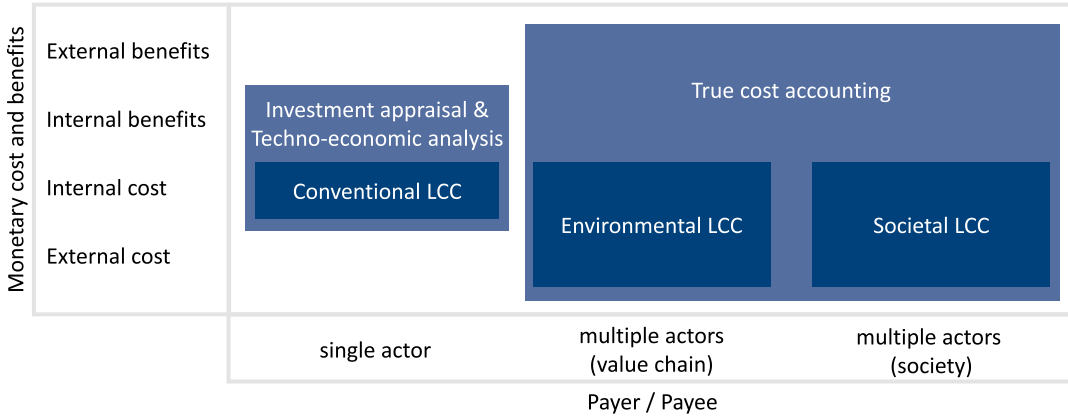
take place in country A, while product distribution and disposal take place in country B. Each step in this value chain is associated with labour, expressed in hours worked per functional unit (FU). The indicator assessed is child labour. Data on child labour is publicly available, but in this example, it is only available at country level and not at country-sector level. This means that processes taking place in the same country are weighted equally for this indicator, even if they belong to different sectors. The last row in ◘ Fig. 41.6 shows the results in medium risk hours per FU. As can be seen from this example, the results can be improved if data are available for the indicators at the country-sector level. Careful interpretation of the data used, and the results is important when carrying out such an assessment. While this example shows only one indicator for child labour, social assessments typically include many indicators to cover a wide range of social issues. A review of indicators used for social assessment of bio-based value chains is presented in Marting Vidaurre et al. (2020)

Impact pathway assessment is based on cause–effect chains. An inventory indicator or social stressor is translated by a characterisation factor into a mid-point impact and/or to an end-point impact (Benoît Norris et al. 2020). As in environmental LCA, characterisation factors need to be scientifically sound. Despite the relevance of this impact assessment method in the field of S-LCA, its development has been slower than that of reference scale assessment. It is, therefore, less used in practice. Examples of modelled cause-effect chains have been reviewed by Ugaya et al. (2023).

The recently published standard ISO 14075 is the first standard for conducting S-LCA (ISO 2024). It has been developed as a guide to best practice.

41.4 Economic Assessment Methods

Economic assessment methods are essential tools to evaluate the sustainability performance of products, services or systems in monetary terms. This may include internal and external cost as well as benefits, depending on the respective method (◘ Fig. 41.7). For instance, investment appraisals (see ► Chap. 16) commonly include internal cost and benefits only. Life Cycle Costing assesses only cost (not benefits), essentially internal cost, but also external cost at value chain or societal level, depending on the type of LCC (see ► Sect. 41.4.1.). The most comprehensive method is *true cost accounting*. This method may include both internal and external costs and benefits (see ► Sect. 41.5.3).



◘ **Fig. 41.7** Classification of economic assessment methods based on inclusion of monetary cost and benefits, and actor involvement

41.4.1 Spotlight: Life Cycle Costing

Life Cycle Costing (LCC) is a method used to evaluate the total cost of ownership of a product, service or system over its entire lifespan. Besides initial cost (capital expenditures for acquiring and implementing the technology or practice), the operation cost (ongoing expenses for energy, labour and materials as well as the maintenance) and the end-of-life costs (e.g. disposal costs for decommissioning and recycling) are also considered (Ciroth et al. 2016). It commonly does not include monetary benefits (e.g. revenue).

According to Swarr et al. (2011), there are three different types of LCC approaches: Conventional Life Cycle Costing (LCC), Environmental Life Cycle Costing (eLCC) and Societal Life Cycle Costing (sLCC). Conventional LCC is a common method used by governments and companies, focused on evaluating the economic costs associated with a product. This approach considers the costs that a specific stakeholder, typically the user of the product, directly incurs. It primarily aims to assist in decision-making for purchasing significant investments like capital goods and durable products. However, it often overlooks external costs that fall outside the direct financial responsibility of the parties involved (see ► Sect. 28.2.1.1).

Environmental LCC (eLCC) expands the conventional approach by including all costs linked to a product's lifecycle. This includes expenses borne by various stakeholders along the value chain, such as manufacturers and consumers. Crucially, it also accounts for external costs that are expected to be internalised in the near future. These costs must reflect actual financial transactions (e.g. a carbon tax, see ► Sect. 27.5.1). eLCC follows the procedure of environmental life cycle assessment, e.g. by using the same scope and inventory. Therefore, eLCC complements LCA by providing a more comprehensive view of sustainability performance as part of LCSA.

Societal LCC (sLCC) goes a step further by monetizing a wide range of external effects, not just environmental but also social impacts, such as effects on social well-being and job quality. sLCC is, therefore, a valuable tool for decision-making at a societal level. It is particularly relevant for governments and policymakers who need to consider the broader societal implications of their decisions (Swarr et al. 2011).

In contrast to LCA, LCC is not a standardised method. It is mostly applied in the scientific context, whereas in the business context investment appraisals are more common (see ► Chap. 26).

41.5 Communication of Sustainability Assessment Results

Comprehensive sustainability assessments consider aspects related to the economic, ecological and social dimension of sustainability. The number of assessed midpoint indicators oftentimes exceeds a manageable single-digit amount. The interpretation of this multitude of indicators is challenging, especially as the relevance of the individual indicators and their interrelations with other indicators (e.g. trade-offs) are not reflected in the assessment results yet. While this level of complexity may become overwhelming, there are further assessment steps that facilitate the interpretability and communicability of sustainability information.

As Bioeconomy systems are embedded in larger social–ecological and socio-economic systems with differing environments and stakeholder perceptions, it is crucial to contextualise sustainability information and to put them into perspective for meaningful decision support. In this section end-point indicators, multi criteria decision analysis (MCDA) and True cost accounting (TCA) are introduced as decision support tools that aim to reduce the level of complexity of the generated sustainability information.

41.5.1 Midpoint Versus Endpoint Results

The LCIA process uses science-based characterisation models to convert inventory data into impact category indicators. These models establish cause–effect relationships between emissions/resource use and their potential impacts on the environment (e.g. ecosystems) or humans (and their health).

For instance, a possible (simplified) cause–effect chain resulting from the emission of greenhouse gas emissions could look like as follows (Rosenbaum et al. 2018)

- Emission of greenhouse gas emissions, e.g. carbon dioxide and methane and their transport & distribution in the atmosphere
- Increased atmospheric temperature (due to increased radiative forcing)
- Increased sea level rise and increased occurrence of extreme weather events
- Floodings and droughts, with their potential impacts on ecosystems and human health

Depending on how far such a cause-effect chain is considered, two approaches are distinguished in LCIA (Rosenbaum et al. 2018):

- ***Midpoint indicators*** focus on intermediate impacts in the cause–effect chain. In the simplified example, this would be reflected by the second level, increased radiative forcing and/or increased atmospheric temperature (e.g. measured as kg CO_2eq).
- ***Endpoint indicators*** focus on the final consequences that an emission of GHGs can have on areas of protection like human health and ecosystem quality. As such, they measure the damage at the end of the cause–effect chain. In the simplified example from above, this would account for the damage done to e.g. ecosystems by floods and droughts. Examples of endpoint indicators include disability-adjusted life years (DALYs) for human health impacts and species loss for the quality of the natural environment. In addition, natural resources are often also considered as an area of protection for which endpoint indicators are calculated.

Depending on the goal & scope, both approaches can be used to communicate about environmental impacts. The choice between midpoint and endpoint indicators depends on the specific needs of the study, the intended audience and the desired balance between detail and simplicity in communicating environmental impacts. For now, midpoint indicators are in practice more often used as they are closer to the source of the impact and provide more detailed insights into specific environmental issues. However, endpoint indicators can also be beneficial as they can provide relevant information to decision-makers with typically only three main categories in scope (ecosystem quality, human health and resource availability/depletion) (Huijbregts et al. 2017).

41.5.2 Multi-Criteria Decision Analysis

MCDA is a set of methods used to evaluate, rank and select among alternative options based on multiple criteria. It is used in sustainability assessment to address complex decision problems with conflicting objectives, diverse data and high uncertainties. The unique characteristic of MCDA is stakeholder engagement. Within a decision-making process, MCDA enhances sustainability information by following an inter- and transdisciplinary approach (► Chap. 37) with active participation of stakeholders, such as researchers, practitioners, residents and policymakers. The sustainability information is contextualised and reflected with perspectives from these stakeholders. The goal of MCDA is to identify conflicting interests, facilitate exchange and find common ground (Kopfmüller and Rösch 2021).

In practice, the criteria considered in MCDA are environmental, social and economic indicators, as well as other indicators (e.g. product quality indicators). During a structured procedure, the indicators are weighted by a stakeholder panel. This weighting allows the integration of all criteria into a single score result. Based on these single score results, decision alternatives can be ranked.

MCDA methods are flexible and versatile approaches, mostly including the following components (Estrada et al. 2022):

1. Problem statement, goal definition and identification of stakeholders
2. Establishment of alternatives, selection of performance criteria and scoring techniques
3. Criteria scoring of stakeholder panel and development of weighting factors
4. Aggregation to single score and ranking of alternatives
5. Interpretation of results (compare and conduct sensitivity analysis)

Stakeholder workshops in combination with surveys are common formats of MCDA. The procedure is accurately documented to ensure a transparent decision-making process. The indicator results at stake within a MCDA originate from various sources and methods, such as LCA, S-LCA and LCC, as well as other qualitative or quantitative methods. MCDA can also be supported by software, such as the Helmholtz MCDA Tool (HELDA). More information ► here.

While MCDA is a strong tool for contextual decision-making, the simplification of complex problems into a structured approach can lead to oversights or oversimplification. Additionally, as assigning weights to criteria is based on subjective judgements of the stakeholders, a balanced panel is fundamental for developing socially optimal recommendations.

41.5.3 True Cost Accounting

True Cost Accounting (TCA) is a comprehensive approach designed to capture the full range of environmental, social and economic costs associated with a product or service. Unlike traditional accounting methods, which often overlook externalities (see ► Sect. 28.2.1.1), TCA provides a holistic view by internalizing these external costs into the price of goods and services. This approach is particularly relevant in bioeconomy, where sustainable resource management is crucial (Baker et al. 2020; Gemmill-Herren et al. 2021).

The monetisation approach in TCA involves assigning monetary values to various externalities. This process begins with identifying externalities, such as greenhouse gas emissions, water usage, biodiversity loss and social impacts on communities. Once these impacts are identified, they are valued using methods like contingent valuation, shadow pricing and cost–benefit analysis. For instance, the social cost of carbon can be used to monetise the impact of carbon emissions. Finally, these monetary values can be integrated into financial statements to reflect the true cost of production and consumption. This integration helps businesses and policymakers make informed decisions that account for long-term sustainability (de Adelhart Toorop et al. 2021). Especially for the agricultural sector, several standards have been developed, such as the True Price assessment method for Agri-Food products from the True Price Initiative (Galgani et al. 2023) or the True Cost Accounting Agrifood Handbook by True Cost Initiative (2022).

TCA offers several advantages. By considering all costs, it enables more informed and sustainable decision-making. TCA also increases transparency by highlighting the hidden costs of production, fostering greater accountability among businesses. Additionally, by reflecting the true costs of unsustainable practices, TCA incentivizes businesses to adopt more sustainable methods. Policymakers can use TCA data to design regulations and incentives that promote sustainability (Baker et al. 2020). However, TCA also has its challenges. It requires extensive data collection and analysis, making it complex and resource-intensive. The methods used to monetise externalities can be subjective, leading to variability in valuations. Integrating TCA into existing accounting and reporting frameworks can be challenging for businesses, and there may be resistance due to perceived increased costs and operational changes (Baker et al. 2020; Gemmill-Herren et al. 2021).

Despite these challenges, there are several compelling examples of TCA in practice. In a large study, Michalke et al. (2023), in collaboration with the German retailer Penny, assessed

the true costs of various agricultural products. On an organisational level, the ABN AMRO Bank applied the TCA approach to the agricultural and other sectors. Furthermore, there are various other examples where the TCA approach also was used on a country, investment or farm level (Baker et al. 2020).

A subfield of TCA that is particularly relevant in the field of Agriculture and Bioeconomy is Ecosystem Service Valuation. Assigning economic value to the benefits provided by ecosystems, such as clean water, air, pollination and climate regulation, facilitates the recognition and incorporation of the economic contributions of natural systems into decision-making processes (Potschin et al. 2016).

The contributions of natural systems can be categorised according to Potschin et al. (2016) into three groups: Provisioning services, which cover products obtained from ecosystems, like food and water; regulating and maintenance services, which cover benefits from ecosystem processes, such as climate regulation and flood control; and cultural services, which include non-material benefits such as recreational and spiritual values (see ► Excursus 6.4).

Methods for valuing these services include market pricing, contingent valuation, and benefit transfer (Kiefer et al. 2023). Ecosystem Service Valuation highlights the economic importance of biodiversity and healthy ecosystems, promoting their conservation and sustainable use. Currently, farmers are only paid the value of the biomass they produce. However, studies show that the value of the other ecosystem services provided by farmers can be substantially higher (von Cossel et al. 2020). ► Excursus 3.1 uses the example of Miscanthus to show how cropping systems have multiple functions and provide ecosystem services beyond the mere provision of biomass.

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41.6 Sustainability Assessments of Bioeconomy Systems

Due to the finite nature of our planet, a sustainable economy and society is the far-reaching goal that enables the next generations to thrive and live in peace on this planet. To achieve this goal, a sustainable circular bioeconomy is part of the solution for various challenges humanity is facing (see ► Chap. 1). However, as *bioeconomy systems are not sustainable per se*, the transformation towards a bioeconomy requires decision support and monitoring (GBS 2015; FAO 2016).

► Relevance of Sustainability Assessment in the Bioeconomy: The Example of Bioenergy and Plant-Based Diets

The controversial discussions surrounding the topic of modern bioenergy, an important sector of the bioeconomy (see ► Chap. 24), provide a recent example why sustainability assessment is relevant. Although the introduction of advanced bioenergy in Europe has been a success story with regard to the achievement of the GHG emission reduction goals (about 64 million tonnes of CO_2-equivalent emissions were reduced through bioenergy in Germany, 25% of the German GHG reduction goal), it requires subsidies to be economically viable (see ► Sect. 28.4). In addition, the reputation of bioenergy is suffering from the possible competition between food and fuel production (Lewandowski 2015). The development of bioenergy has been accompanied by many unintentional and unanticipated environmental, social and economic side effects and trade-offs that could have been at least partly discovered by ex-ante sustainability assessments and then considered within the design of policy measures.

A positive example that showcases the relevance of sustainability information can be seen in the field of plant-based diets. Sustainability assessment results have consistently highlighted the benefits of reducing animal-based food consumption. Studies show that plant-based diets require fewer natural resources, such as land and water, and produce significantly lower greenhouse gas emissions compared to meat and dairy-heavy diets. By quantifying these impacts, sustainability assessments make clear the potential of plant-based eating to mitigate climate change, reduce biodiversity loss and improve global food security. As a result, they have become a cornerstone of recommenda-

tions for sustainable dietary practices, encouraging a shift toward plant-based alternatives (Viroli et al. 2023). This contributes to a noticeable shift in consumption patterns, reflected, for example, in the growing demand for plant-based meat alternatives (see ▶ Chap. 21). ◀

Due to the complexity of bioeconomy systems, the transformation towards a sustainable bio-based economy requires science-based information to guide the decision makers towards sustainability. In this context, sustainability assessment is a powerful process to generate *sustainability information*.

Sustainability Assessment of bioeconomic activities should

- Be based on *life cycle thinking* to identify their effect on the bioeconomy system as a whole and avoid isolated optimisation of specific activities. Improvement of one life cycle stage may not come at the cost of negative consequences for other parts of the system, which may outweigh the advantages achieved (e.g. avoid competition leading to food supply problems).
- Follow a *conceptual framework* with contextual elements that consider stakeholder perspectives.
- Include a *materiality analysis* and find a balance between economic, environmental and social aspects, as well as respective quantitative indicators.
- Commonly be performed *ex-ante*. This means well in time to serve as decision support for the planning of the activity, provide information for the discussion process with stakeholders and highlight "future" problems such as negative impacts that will become apparent in the future, for example, global warming effects.
- Provide sustainability information regarding *hot spots* in, and *trade-offs* among the selected environmental, social or economic aspects.

The complexity of the assessed systems requires a whole set of methods and tools that work together. One approach alone cannot deal with the manifold challenges that need to be faced when assessing bioeconomy systems. This "sustainability assessment toolbox" includes, besides assessment methods and indicator frameworks, also other modelling approaches that can predict the behaviour of bioeconomy systems (see ▶ Chap. 42).

A look at different levels of assessment illustrates the use of this toolbox and highlights key challenges:

Technological Level

Sustainable bioeconomy is an innovation-driven paradigm (see ▶ Chaps. 32 and 33). In this context, technological readiness is an important consideration when conducting sustainability assessments. Laboratory-scale data on a process may not match the performance of a pilot- or industrial-scale production unit. This aspect is particularly relevant when comparing bioeconomy approaches with other non-bio-based state-of-the-art approaches or technologies. The state-of-the-art technology may have undergone decades of continuous improvement, whereas the innovative bio-based alternative may not. Compared to the impacts of the lab-scale system, the impacts after scale-up are mostly lower (Thonemann et al. 2020). Appropriate up-scaling methods should, therefore, be used in the assessment to ensure a level playing field, e.g. techno-economic analysis (Götz et al. 2022, 2023). Not only can technology evolve over time, but the socio-economic system around us is also constantly changing. Economic trajectories need to be taken into account when assessing the sustainability of future bioeconomy systems. Prospective LCA is an emerging field of research that aims to take this into account (Mendoza Beltran et al. 2020; Langkau et al. 2023).

Value Chain Level

The value chain perspective is a pivotal concept in bioeconomy development (see ▶ Chap. 4). In the design and development process, selecting biomass-to-product pathways with most promising sustainability performance is crucial (Vargas-Carpintero 2025). Sustainability assessment of bio-based value chains applies life cycle thinking, while each life cycle stage has its own challenges:

- Primary production in agricultural systems for instance is highly complex on its

own. Most production systems are open systems. Various emissions are associated with agriculture, such as nitrous oxide, ammonia, nitrate and methane, causing considerable environmental damage. Those emissions are estimated by means of emissions factors, biophysical or statistical models (Zampori and Pant 2019; Weik et al. 2022).

- Secondary feedstock for the bioeconomy, such as biomass from residual and organic waste streams (see ▶ Chaps. 12 and 13), requires a systemic view with respect to resource competition, as often these secondary feedstocks are already in use (Ghafghazi et al. 2017). For instance, spent yeast from brewing process can be used as feedstock for protein production. As spent yeast is currently used as feed additive (Hejna 2022), the assessment must consider the consequences of repurposing the yeast usage. Considering the demand for feed stays constant, the yeast will be replaced with a substitute. This consequential approach, as promoted in consequential LCA (Brandão et al. 2024), requires the understanding of the underlying economic systems and its dynamics (see ▶ Chap. 42).
- During biomass conversion processes commonly by-products emerge, such as lignin, glycerol or organic residues. Assessing product systems with multiple outputs is challenging, particularly if the impact of a specific product should be identified. In LCA, this is called the *multifunctionality problem.* It can be solved in various ways, such as subdivision, system expansion and substitution or allocation (ILCD 2010; Guinée et al. 2021) (See ◘ Supplementary Material 41.5).
- Carbon sequestration and storage is an important process throughout the life cycle of bio-based products. During primary production, carbon is sequestered within the soil and the below- and aboveground biomass. Carbon storage is particularly relevant for climate change mitigation (see definition of biogenic carbon accounting). A crucial component in carbon storage is time. While carbon is ideally removed permanently from the atmosphere, most processes within bioeconomy are more dynamic. For instance, the carbon stored within the soil might be released due to land use change rather fast, the temporary storage in products, however, delays carbon release into the atmosphere. There are different methods to account for delayed carbon release, such as modelling carbon pools (Blujdea et al. 2022), or dynamic biogenic carbon accounting (Levasseur et al. 2013).
- In a circular bioeconomy, a products' end-of-life is the beginning of the next use, following the principle of cascading use. For the sustainability assessment, the questions must be raised about what impacts of the previous life cycle are relevant for the next cascade. In this context, two approaches are available: The cut-off approach and the allocation at the point of substitution, short APOS approach (Wernet et al. 2016). In the cut-off approach, all environmental impacts are assigned to the system that produces the primary material or product until it leaves that system. When a material is recycled, its environmental burdens are "cut-off" from the upstream system and not passed on to the downstream user (polluter pays principle). As a result, recycled materials are considered burden-free for subsequent use. This method incentivizes the use of recycled materials by reducing their apparent true cost. However, it neglects the shared responsibility between the producer and user of recycled materials and may underestimate the sustainability benefits of recycling. These aspects are better represented by the APOS approach. It allocates sustainability impacts based on the substitution principle, where recycled materials or by-products are seen as substitutes for virgin materials. This means that the environmental benefits of avoiding virgin material production are shared between the producing and consuming systems. The APOS approach better reflects the circularity benefits of recycling but is more complex, requiring assumptions about substitution ratios and avoided impacts. Learn more about system models ▶ here.

Biogenic carbon refers to carbon that is naturally cycled through living organisms, such as plants, trees and biomass in general. The amount of carbon in biomass is typically around 50% of its dry mass. During primary production, this carbon is bound from the carbon dioxide in the air through photosynthesis (see ► Sect. 5.1). Biogenic carbon is the reason why the bioeconomy is seen as a key strategy for mitigating climate change. Increasing the natural carbon pools of living biomass and bio-based products actively reduces the carbon dioxide concentration within the atmosphere (Zhao et al. 2022). In addition, bio-based products can substitute products based on fossil carbon, and this way reduces additional fossil carbon release.

Biogenic carbon accounting is essential for evaluating the effect of bio-based products and systems on climate change. This process tracks the uptake of carbon dioxide during biomass growth and its release after the cultivation phase, during processing, use or end-of-life stages. This enables the assessment of carbon neutrality or net emissions. Proper accounting ensures transparency in greenhouse gas assessments and helps to quantify the climate benefits of substituting fossil-based products with renewable, bio-based alternatives.

■ Territorial Level

Territorial sustainability assessments are used, for instance, to assess the effects of a policy or the large-scale implementation of a bioeconomy approach on the regional or national economy and related environmental and social effects. It considers the broader spatial dynamics, such as resource availability and land use and accounts for regional characteristics like soil quality, biodiversity and socioeconomic factors. Adding spatiality to the assessment implies further consideration, e.g. regarding region-specific impacts. Field emissions, for instance, highly depend on management and location factors and vary across regions. Also, some sustainability indicators cover global impacts, such as climate change, i.e. it does not matter if carbon is released to the atmosphere in region A or region B, the effect on the carbon content in the atmosphere and global warming is the same. Other indicators, such as human toxicity, are more related to the regional context, i.e. if toxic emissions are released within an area of low population density their damage is lower than emitted within an area with a high population density.

These examples underline that sustainability is highly context specific. The transferability of results from one system to another is often limited (Ding et al. 2023; Loiseau et al. 2018; Nitschelm et al. 2016). Territorial assessments commonly require the coupling of various tools and models (e.g. Ding et al. 2023; Weik et al. 2022) or integrated assessment models (Vargas-Carpintero 2025) (see ► Sect. 42.2.4).

Do you want to learn more about the sustainability assessment of bioeconomy regions? Take a look at ◘ Supplementary Materials 41.6 and ◘ 41.7, two videos from our MOOC "Concepts of Sustainable Bioeconomy" (2021).

Questions

1. Name and describe the six stages of a product's life cycle using an example.
2. Briefly describe the three methods included in Life Cycle Sustainability Assessment.
3. Explain the sentence "Bioeconomy systems are not sustainable per se" by means of an example.

Answers

1. The life cycle of a bamboo toothbrush consists of six stages, highlighting its journey from cradle to grave. (1) Extraction of Raw Materials: Bamboo is harvested as the primary material for the toothbrush handle, while the bristles are made from bio-based or syn-

thetic materials. (2) Design and Production: The bamboo is shaped into handles, and bristles are attached to create a functional and simple toothbrush. (3) Packaging: Sustainable packaging, such as recycled paper, is used to minimise waste. (4) Distribution: The toothbrush is transported to stores or consumers, with brands often focusing on reducing shipping emissions. (5) Use Phase: The toothbrush is used like any other toothbrush, offering effective oral hygiene for several months. (6) End of Life: The bamboo handle can be composted, while bristles may require separate disposal depending on the material.

2. Life Cycle Sustainability Assessment (LCSA) includes three methods to evaluate a product's overall sustainability: (1) Life Cycle Assessment (LCA) focuses on environmental impacts, such as carbon emissions and resource use. (2) Social Life Cycle Assessment (S-LCA) evaluates social impacts, including worker conditions and community well-being. (3) Life Cycle Costing (LCC) examines the economic costs across the product's life cycle, from production to disposal.
3. The sentence "Bioeconomy systems are not sustainable per se" means that bioeconomy systems are not automatically sustainable just because they use renewable resources. Sustainability depends on how these systems are managed and whether they take into account environmental, economic, and social factors. Consider a bioeconomy system focused on producing biofuels from crops like corn. While biofuels are renewable and can reduce reliance on fossil fuels, this system may not be sustainable if it leads to deforestation for crop production, soil depletion, or excessive water use. If these negative environmental impacts are not managed properly, the system may harm ecosystems and communities, even though it uses bio-based resources. Thus, the system would not be considered sustainable.

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Modelling to Support the Bioeconomy Transition

Christian Sponagel, Jan Weik, Christian Troost, and Elisabeth Angenendt



Fig. 42.0 Modelling to support the bioeconomy transition. © Christian Sponagel (► https://doi.org/10.1007/000-hvq)

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Decision-makers are facing the challenge of balancing different factors in the midst of an increasingly complex world. The development of appropriate strategies and policy instruments requires information on system behaviour. Modelling and data-driven decision support tools have become essential for this task, turning vast data into actionable insights. By capturing system dynamics, these tools optimize resource allocation and provide a comprehensive view of interconnected processes, helping navigate complex systems with greater precision. This chapter begins with a general definition of models and their scope of application. It highlights the need for modelling to understand and predict the behaviour of human and natural systems within a developing bioeconomy. An overview of the main types of models at different scales of decision making is provided as well as an introduction to scenario development and its application.

Learning Objectives

After studying this chapter, you will…

- …be able to explain the concept of modelling and their role within the bioeconomy (see ► Sects. 42.1 and 42.2).
- …be able to classify the most important model types at the various decision-levels of the bioeconomy (see ► Sects. 42.2.1, 42.2.2, 42.2.3, and 42.2.4).
- …be able to describe methods of scenario development and their application (see ► Sect. 42.3).

42.1 Introduction to Models and Modelling

The complexity of our world is steadily increasing due to several interconnected factors. Globalization has created tightly interwoven economies and industries, where decisions in one region impact others, making global dynamics more unpredictable. Technological advancements, such as digitalisation and artificial intelligence, present new opportunities but also add complexity by requiring constant adaptation as well as raising ethical and security concerns. Environmental challenges, such as climate change, biodiversity loss and resource depletion, further complicate decision-making as organizations and governments strive to balance growth with sustainability. At the same time, societal and demographic shifts, including aging populations and urbanization, place growing demands on infrastructure, healthcare and social systems, often leading to conflicting priorities. Political and economic instability adds another layer of uncertainty, with shifting power dynamics and rising inequality creating a volatile global landscape.

In this highly complex world, decision-makers at various levels must consider multiple factors simultaneously. The ability to manage and respond to complexity is now more than ever essential for effective decision-making and long-term sustainability. Achieving this requires a deep understanding of the systems and processes influenced by their decisions. This is where modelling plays a vital role, as it transforms vast amounts of data into actionable insights.

Data-driven models for decision support capture system dynamics and thus provide a clearer understanding of the systems being analysed. These models offer a comprehensive view of interconnected processes, allowing decision-makers to address challenges with greater precision.

> "A ***model*** can be defined as an analytical representation or quantification of a real-world system, used to make projections or to assess the behaviour of the system under specified conditions" (Acs et al. 2019).

A model does not stand alone. It is in relation to a real system, the original system, as well as the perspective and intentions of the developer or user. This results in a relationship triangle consisting of the model developer or model user (model subject), the real system that is to be represented by the model (model object) and the model itself (see

Fig. 42.1). In the relationship between model subject and model object, the scope of the system or subsystem to be modelled is just as relevant as the subject's goal (Töllner 2009).

The scale level of the model object determines the degree of abstraction of the model to be developed (Plieninger et al. 2016). For example, the cultivation of agricultural biomass for the bioeconomy cannot be considered with the same degree of differentiation in a world trade model as in a farm model.

The goal of the model subject determines the intention of the model. These intentions are varied and include system description, explanation and demonstration, mathematical calculations, experimental investigations, planning and design, improvements, simulation, prediction and decision support (Töllner 2009).

The intention of the model determines its application in time. For instance, models can make distinct contributions to the analysis of the various implementation stages of policy (see Fig. 42.2) (Verburg et al. 2016). *Goal-oriented modelling* intends to show what the world should or could be like and which political measures/instruments can be used to achieve these goals. *Ex-ante assessments* are used to analyse the effects of political measures in advance. This allows potential conflicts of interest to be identified even before the measures are implemented. The visualization of the results of different future scenarios can help decision-makers to discuss and, if necessary, adjust the objectives of measures. Optimization models are used for this purpose, particularly in the field of environmental policy measures, which examine future framework conditions regarding socio-ecological goals (Verburg et al. 2016; Helming et al. 2011). *Ex-post assessments* are used to evaluate an implemented policy measure. Econometric models and methods are often applied for this purpose (Verburg et al. 2016). This can show the actual impact, efficiency or the costs and benefits associated with the measure. The results can also be used to identify possible weaknesses and unintended induced effects of the analysed policy measure. Building on this, *exploratory scenario simulation* supports policymakers in problem

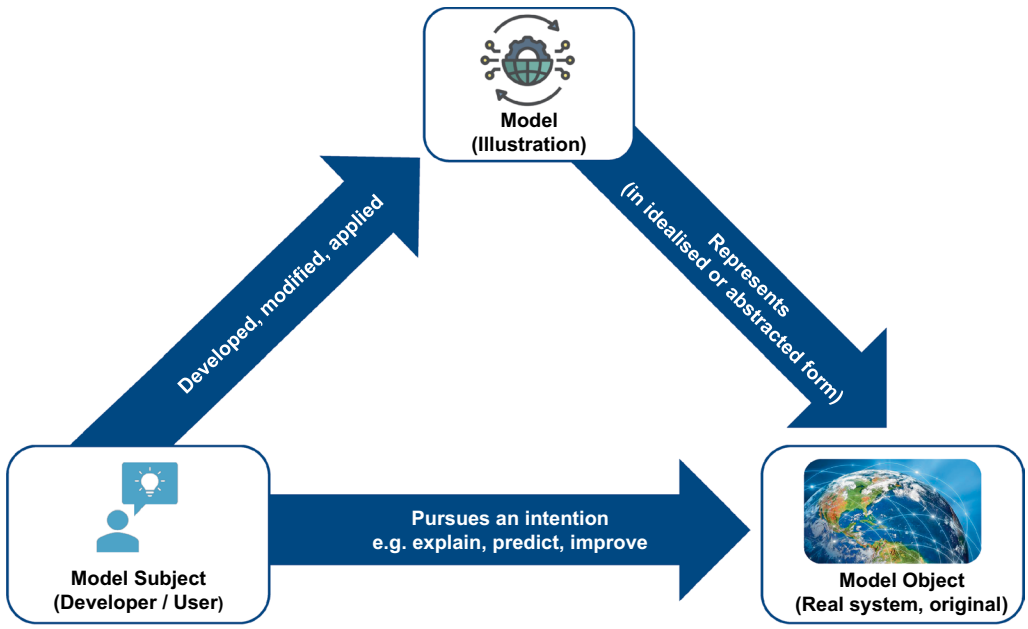


Fig. 42.1 Relationship triangle of model development and application. (Based on Töllner 2009)

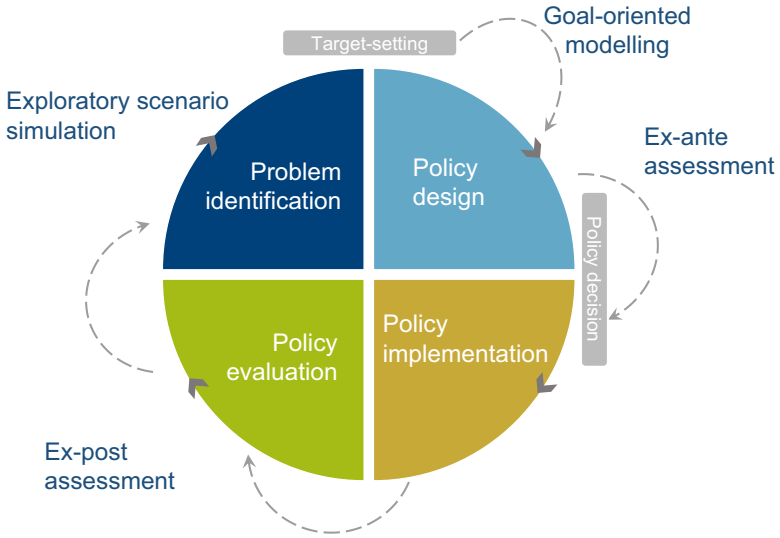


Fig. 42.2 Contribution of model-based analysis at different stages of policy design and implementation. (Based on Verburg et al. 2016)

identification and the development of more targeted measures or policy instruments.

It is important to demonstrate that the various models work correctly and that the results are sufficiently accurate, if they are to be used in a meaningful way. To provide this evidence, the models need to be verified and validated (Sargent 2010). The purpose of *model verification* is to check that the model has been implemented correctly and meets the specified requirements. The aim is to ensure that the model has been implemented correctly, both technically and mathematically. This includes, for example, checking that the model code is correct and does not contain technical errors, or that the algorithms have been implemented correctly. The purpose of *model validation* is to show whether the model can be used in practice and is suitable for the intended purpose. The aim is to assess whether the model accurately represents the real system or process and provides reliable results. This includes, for example, checking whether the model predictions are consistent with real data and observed results, whether the model produces the desired and relevant results and whether it is robust and reliable under different conditions (inter alia: Sargent 2010; Oberkampf and Trucano 2008; Kleijnen 1995).

> ***Verification:*** "Have we built the model right?" Focuses on the correct implementation and technical/mathematical correctness of the model. It ensures that the model does what it is supposed to do.
>
> ***Validation:*** "Have we built the right model?"
>
> Can the model or simulation adequately support the intended use? Is its fidelity appropriate? Focus on the accuracy and applicability of the model for its intended use. It ensures that the model does the right thing (Pace 2004).

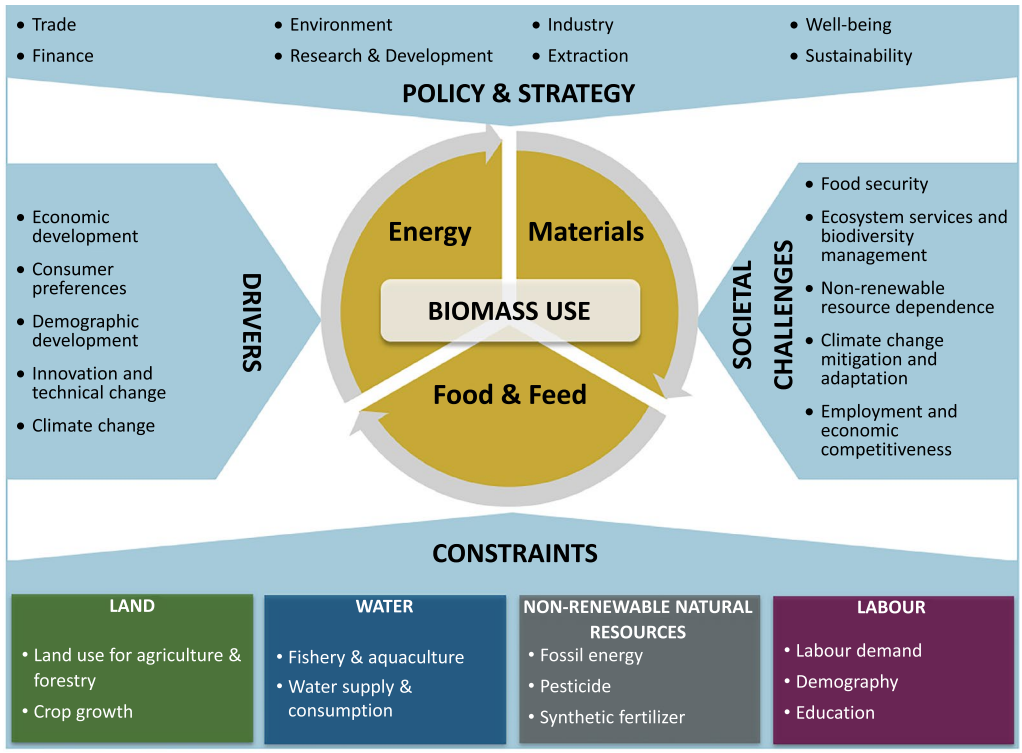
In recent decades, the number of models used for decision-making in the bioeconomy has increased rapidly. The following sections introduce the wide range of models that are used in this context (see ► Sect. 42.2) as well as relevant data sources (see ► Sect. 42.4). An

important aspect of modelling, especially for ex-ante assessments, is scenario building (see ▶ Sect. 42.3). ▶ Section 42.5 briefly highlights the limitations of modelling.

42.2 Modelling the Bioeconomy

The bioeconomy spans a wide range of sectors, such as agriculture, energy and the processing industry. Their development is influenced by a multitude of surrounding factors that must be considered when modelling the bioeconomy. This includes the policy and strategy context, drivers, such as demographic development or consumer preferences, societal challenges, for instance, food security, as well as natural (e.g. water or land scarcity) and socioeconomic constraints (e.g. labour demand) (see ◘ Fig. 42.3) (van Meijl 2015).

Modelling in the bioeconomy provides a structured way to understand, predict and shape the complex interactions within a bio-based economy. Models apply a data-driven approach to examine bioeconomy systems and show how changes in biomass use might impact, for instance, carbon emissions, food prices or biodiversity. This information helps decision-makers navigate toward sustainability goals.



◘ **Fig. 42.3** Conceptual framework for modelling bioeconomy systems. (Based on van Meijl (2015))

Excursus 42.1. How Is Modelling and Sustainability Assessment Related?

Modelling and sustainability assessment have in common that they both provide information to support decision-making. Often it is not easy to draw a clear line between the two topics. For example, life cycle assessment, a well-known sustainability assessment method, involves different aspects of modelling. The product system is a model of the real system. This model is quantified with the life cycle inventory and used to assess the environmental impact of the system. The impact pathways are also based on different biophysical models. On the other hand, typical models, such as CAPRI, provide important sustainability information, such as greenhouse gas emissions and farm income.

So, what is the difference? While economic or biophysical models can predict the behaviour of a system, sustainability assessment methods are usually more comprehensive, covering more sustainability aspects and related indicators. The use of impact indicators and their aggregation is also more common in sustainability assessment methods. This improves the communicability of the results.

In conclusion, modelling and sustainability assessment are closely linked. Models enable sustainability assessment, and sustainability assessment provides a comprehensive framework for making informed decisions. In both fields, this interdependence is further developed. For example, prospective LCA requires results from foresight modelling (Mendoza Beltran et al. 2020) and consequential LCA uses information from economic models to identify the marginal consequences of a production process (Marvuglia et al. 2013). At the same time, many integrated assessment models include further sustainability indicators such as biodiversity (Philippidis et al. 2024).

Models play a critical role in supporting policy decisions related to the bioeconomy, for example in the European Union (EU). With the European Green Deal and other sustainability goals in place, models have become essential tools for evaluating scenarios, assessing policy impacts, and guiding the EU's transition towards sustainable development. In this context, models can make a valuable contribution to the analysis of potential scenarios of a future bioeconomy (Verkerk et al. 2021).

Effective modelling of the bioeconomy requires the integration of economic, social and environmental sustainability dimensions, comprehensive coverage of sectors, and high spatial and temporal resolution to capture localized impacts. Models need to address emerging challenges such as circularity, technological innovation and consumer behaviour while leveraging big data and AI for enhanced capabilities. Interdisciplinary linkages with life cycle assessment or biodiversity models are crucial to address cross-cutting objectives (Verkerk et al. 2021; Pyka et al. 2022).

However, many models are specialized in single aspects of a system, such as renewable energy supply (BeWhere) or crop growth (CERES). As modelling the bioeconomy needs to take into account different aspects, these efforts have extensive interdisciplinary requirements and involve a high degree of model integration. Currently, there is no modelling approach that can cover all aspects of a developing bioeconomy (O'Brien et al. 2015; Christensen et al. 2022).

At the moment, modelling the bioeconomy involves a whole toolbox of models. They can be broadly characterised according to three main criteria: Purpose, type and approach. The purpose reflects the scope of the model, such as short-term forecasting, medium- to long-term scenario analysis or backcasting to achieve specific future outcomes. The type of model varies widely, including top-down models for broad, system-level analysis; econometric models using historical data for medium- to long-term forecasting and system dynamics models designed to understand complex behaviour over time. Finally, the approach captures the model's handling of uncertainty, with deterministic models providing precise, fixed outcomes, while stochastic and probabilistic

models incorporate varying degrees of randomness to simulate realistic possibilities. More details on this categorisation can be found ▶ here.

The following subsections present a selection of models relevant to analyse the bioeconomy. The categories chosen are classical economic models, agent-based models, environmental and biophysical models, as well as integrated assessment models. ◘ Figure 42.4 provides an overview of the model types presented, and their categorization according to the scale at which the model type is typically applied to. However, due to the close link between economic activity and environmental impacts, the distinction between economic and environmental models is not always as clear-cut as shown in ◘ Fig. 42.4. In addition to the integrated assessment models, there are numerous economic models with specific biogeographical references. Agent-based models and geodata-based economic land use models are also used at various scales. The structure of the following model descriptions should, therefore, not be seen as rigidly economic or environmental but rather as being based on the main application of the respective model.

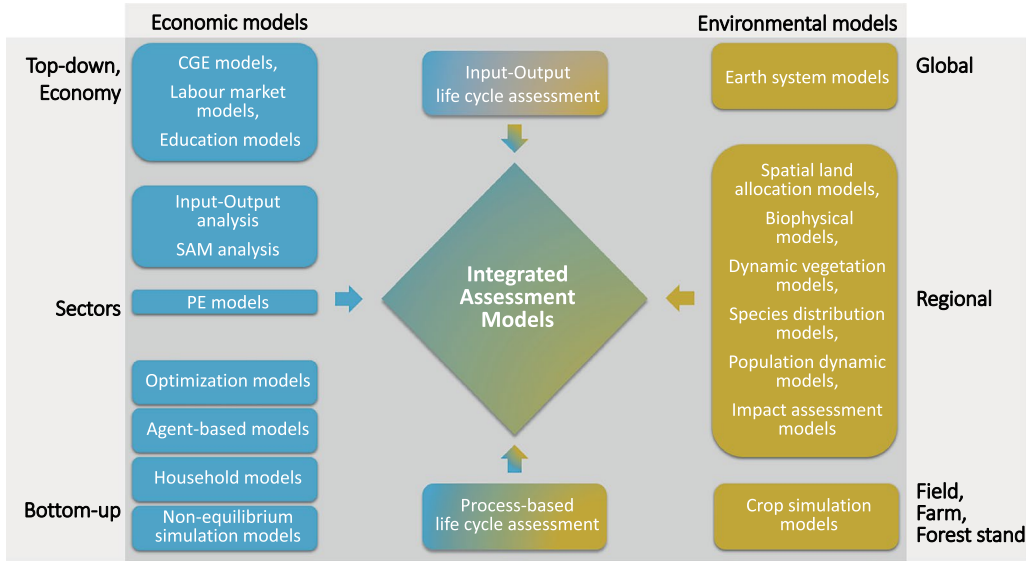
42.2.1 Classical Economic Models

A. **Macroeconomic Models**

A small selection of classical macroeconomic and sectoral models is presented below. The computable general equilibrium (CGE) models listed in the next subsection are based on the general equilibrium theory, an economic theory that is expressed in simplified terms based on an adjusted balance between supply and demand. These models are often used to analyse trade. Partial equilibrium (PE) models are also based on this neoclassical theory, but they focus on a specific market or sector. They are useful for gaining a more detailed understanding of a particular sector.

1. ***Examples for CGE Models***

The *GTAP* (Global Trade Analysis Project) is a global network of researchers conducting quantitative analysis of international policy issues and is coordinated by Purdue University in Indiana, USA. It provides a generalized CGE modelling framework and a comprehensive database used for analysis in other CGE models. The GTAP



◘ **Fig. 42.4** Overview of model types used to analyse the bioeconomy transition. (Based on van Meijl (2015))

standard model is a recursive dynamic CGE model. Its main applications are the analysis of multilateral trade and the impact of trade liberalization. It represents the linkages between sectors such as agriculture and energy and has been extended to the bioenergy sector, in particular ethanol, biodiesel and their co-products; the agricultural residue corn stover; the energy crops switchgrass and miscanthus for second-generation ethanol production and palm oil residues (Wicke et al. 2015). There are numerous model developments that include GTAP in their name. For example, GTAP-Bio, which can be used to analyse the impact of bioenergy on indirect land use change and the associated greenhouse gas emissions (Taheripour et al. 2024). The statistical basis of a CGE is a Social Accounting Matrix (SAM). A SAM is based on a circular flow concept, such as input–output approaches and could therefore be used independently of a CGE for macroeconomic analysis (Poganietz 2000).

There are a number of other CGE models based on the GTAP database, such as MAGNET. MAGNET (Modular Applied GeNeral Equilibrium Tool) is a recursive dynamic CGE model developed at the Landbouw Economisch Institut (LEI; Wageningen University and Research, The Netherlands). It is the successor model of LEITAP (Landbouw Economisch Instituut Trade Analysis Project). It has a modular structure with modules for mapping the EU Common Agricultural Policy (CAP) and biofuels and evaluates long-term, economy-wide upstream and downstream effects including price (van Meijl et al. 2006). MAGNET has been applied to analyse the macroeconomic impacts of bioenergy and biochemical in the Netherlands (van Meijl et al. 2018), the macro-economic impacts of a bio-based economy in Malaysia (van Meijl et al. 2012) and the global leakage effects of EU biofuel consumption (Smeets et al. 2014). More recently, MAGNET has been expanded to include additional bio-based sectors, such as second-generation biofuels, bioelectricity, biochemicals and biomass supply sectors, both for agricultural and forestry residues and for pretreatment of agricultural residues used by other sectors (Banse et al. 2014). The competition for biomass use that a transition path to a materially bio-based economy would create for food and feed supply can also be easily modelled with Magnet (Sturm and Banse 2021). The model is widely used for EU policy advice.

2. ***Examples for Sector Models***

Sectoral models used to address bioeconomy issues typically focus on the agricultural and forestry sectors. They are used to show the competition for biomass for material and energy use versus food and feed. Due to the importance of biomass use, the focus below is on the agriculture and forestry sectors.

CAPRI (Common Agricultural Regionalised Impact Analysis) is a PE model focusing on the agricultural sector in Europe. It has been developed to assess the ex-ante impacts of the EU Common Agricultural Policy and trade policies on agricultural production, incomes, markets, trade and the environment from a global to a regional scale. CAPRI can analyse a wide range of policy measures, taking into account agro-environmental impacts. The comparative-static economic model is divided into a supply module and a market module. The supply module consists of independent non-linear programming models representing the activities of all farmers at the regional or farm-type level, as recorded in the Economic Accounts for Agriculture. The market module provides the prices used in the supply module and allows market analysis at global, EU and national levels as well as welfare analysis. The link between the supply and

market modules is based on an iterative process. These modules are linked to regional CGE models for each European country with a specific focus on rural development measures under the second pillar of the CAP (▶ www.capri-model.org). It is an integral part of the model-building kit used for policy advice by both the European Commission's Joint Research Centre in Seville and the German Federal Research Institute, the Thünen Institute. CAPRI's high reputation has led to it being used for numerous analyses in the context of policy advice (Acs et al. 2019).

ESIM (European Simulation Model) is a global PE model for the agricultural sector representing agricultural production, various processing activities and demand for agricultural products, as well as international net trade. With its comprehensive model of the EU CAP, it is used to analyse EU agricultural and trade policies. It covers the EU Member States and Candidate Countries, the USA and the rest of the world (the latter as a single aggregate). It covers the processing of oilseeds for biodiesel and cereals, sugar beet and sugar cane for bioethanol, the production, use and trade of biofuels, and the production and use of co-products (oilseed cake, gluten feed) in livestock production (Deppermann et al. 2014). The model has been used to analyse various issues related to the use of perennial crops in the bioeconomy (Choi et al. 2019; Choi and Entenmann 2019).

MAgPIE (Model of Agricultural Production and its Impact on the Environment) is a global partial equilibrium model with a spatial resolution of 0.5 × 0.5 degrees. The model has been developed to analyse future global scenarios in the twenty-first century. It follows a modular, open-source framework that allows collaboration between different users. The model takes into account regional socio-economic conditions, such as population and income characteristics, that lead to regional food demand. In addition, regional crop yields are estimated using a dynamic vegetation model linked to MAgPIE, taking into account land and water constraints. The model can also incorporate international trade. A total of 20 crop activities and three livestock activities are integrated into the model. Within the model's objective equation, total production costs are minimized to meet global food and bioenergy demand. Prices are modelled endogenously from the marginal supply costs. The output of MAgPIE can be used to infer regional cropping patterns or water scarcity, among other indicators (Dietrich et al. 2019; Lotze-Campen et al. 2008; Mishra et al. 2021).

GLOBIOM (Global Biosphere Management Model) is a global, economic partial equilibrium model of agriculture and forestry with a high-resolution representation of global agriculture, forestry and land use change. GLOBIOM is spatially explicit, with the spatial resolution of the supply side based on the concept of simulation units, which are aggregates of 5 to 30 arcminute pixels that share the same elevation, slope, soil class and country. Based on the structure of GLOBIOM, several regional model versions have been developed whose spatial resolution can be much higher. The standard version is part of an integrated modelling framework at the International Institute for Applied Systems Analysis (IIASA). The model covers all countries, including aggregations into 28 global regions. Its crop and forest sector details are based on physical parameters provided by more specialized models, G4M for forestry and EPIC (Izaurralde et al. 2012) for agriculture. Global agricultural and forest market equilibria are calculated by choosing land use and processing activities to maximize the sum of producer and consumer surplus subject to resource, technological and policy constraints.

GLOBIOM can be linked to energy models through information on macro-economic indicators and bioenergy demand. The latter is divided into first-generation biofuels, second-generation biofuels, bioenergy crops and direct biomass energy use. Issues analysed with GLOBIOM include the competition for land supply between agriculture, bioenergy and forestry; examples include land use change impacts of bioenergy policies, climate change mitigation options and policies, food-environment trade-offs or global food supply (Kraxner et al. 2013; Janssens et al. 2022). More information can be found ► here.

EFI-GTM (European Forestry Institute-Global Trade Model) is a multi-product, multi-regional PE model for the global forest sector. It integrates growing forest resources, timber supply, wood-using industries (e.g. woodworking, pulp and paper), demand for forest products and wood-based energy, and international trade in forest products. Specifically, the model calculates periodic production, consumption, import and export volumes, and product prices for forest sector products. It has global coverage with a focus on Europe. It also allows for detailed impact analysis of the forest sector and detailed trade effects due to bilateral trade flows. It has been used to address issues such as increased investment in forest plantations in Asia and South America, increased demand for bioenergy, the impact of carbon emission prices and fossil fuel prices on the use of wood biomass for energy and the impact of trade policies and forest conservation policies (Solberg et al. 2003).

The energy sector is another important sector in the context of bio-economic issues. One example is the *JRC EMT* (Energy Trade Model of the EU Joint Research Centre). It is a partial equilibrium model of the global energy system and allows for a cost-effective allocation of a wide range of energy resources and technologies, taking into account the comprehensive energy demand of all economic sectors (Barbero-Vignola et al. 2020).

There are also approaches to special sectoral models for the bio-economy, but these are at an early stage due to data availability. A new analytical tool called *BioMAT* (Bio-based MATerials) has been developed to present stylized value chains of bio-based materials in the EU and its Member States. The focus of BioMAT is on bio-based chemicals (Sturm et al. 2023).

B. **Economic Bottom-up Models**

There are a variety of bottom-up models that can answer a wide range of questions within an overall bio-economic complex. Most of these models analyse very detailed technologies and processes as well as the behaviour of different actors such as farms or energy plants. There are many models that operate at different spatial scales in analysing the availability and supply of biomass and the associated economic and environmental impacts and therefore have well-defined system boundaries in terms of geographical scope, sectoral coverage and technology. These models can provide detailed insight into specific issues. However, bottom-up models are typically unable to generate indirect or induced effects—such as price responses, competition, substitution effects, and technological or structural changes—beyond the relatively narrow system boundaries (Wicke et al. 2015). For such purposes, they would need to be linked, for example, to the CGE or PE models mentioned above. Several examples of economic bottom-up models for different sectors and different levels of disaggregation are provided.

1. ***Examples of Agro-economic Supply Models***

The model approaches presented are suitable for simulating the adaptation responses of farms or regions to changing political or technological conditions. Their methodology consists mainly of mathematical linear or non-

linear programming models that produce the quantity of agricultural products under the relevant conditions. They are often developed for specific problems or locations and are not used after the research projects have ended (Janssen et al. 2010). However, the following models, which are examples of the large number of existing agricultural bottom-up models, are well established in research institutions and have been continuously used and developed for various economic and environmental assessments of agricultural systems. Some farm-based models can be applied at the regional or sectoral level using projection methods.

FSSIM (Farm System Simulator) is an optimization model that maximizes total gross margin under a set of resource and policy constraints. It is a component-based framework with modules for representing farmer objectives, risk, calibration and both agricultural and environmental policy instruments, as well as current, alternative and future production activities. The model is designed as a generic bio-economic farm model. Its flexible design allows it to be used for a variety of climate zones, soil types, farm types, research applications and data sources (Janssen et al. 2010; Louhichi et al. 2010). For example, FSSIM has been applied to 13 regions in the EU and to different farm types. Within SEAMLESS (System for Environmental and Agricultural Modelling; Linking European Science and Society), an integrated modelling approach (see Sect. 42.2.4), FSSIM is used to analyse the farm level (Ewert et al. 2011).

EFEM (Economic Farm Emission Model) simulates agricultural production at micro- (farm) and meso- (regional) levels. It is a supply model based on static linear programming. Producer prices, production costs and capacities for typical farms, are exogenously determined. The model takes into account the most important agricultural production methods in animal and plant production in Germany. The model differentiates on a regional level in terms of yields, intensification, productivity and costs. Data from the Farm Accountancy Data Network (FADN) or survey data can be used to represent the required farm model capacities. The model also calculates greenhouse gas emissions, other nitrogen fluxes and carbon balances from agricultural production (Schwarz-v. Raumer et al. 2017). The model has already been linked to several biophysical models (e.g. Weik et al. 2022). In order to analyse possible development scenarios for the bioeconomy, it has already been coupled with the agricultural sector model ESIM, which allows considering both effects on the EU agricultural market and impacts at the farm level (Petig et al. 2019). Furthermore, EFEM has been used to analyse the economically optimal distribution of straw-to-chemical value chains at the federal state level through a coupling with the techno-economic location optimization model (Petig et al. 2018).

Because agricultural production is so closely linked to interactions with the natural environment, economic land-use models have been increasingly developed in recent years. They can handle a high degree of complexity and are therefore useful for analysing the outcomes of different land use scenarios in terms of economic or environmental indicators, among others (Brouwer and Ittersum 2010; Agarwal et al. 2002). Analyses can be carried out at a wide range of spatial scales, from local to regional, with different spatial resolutions, such as the field level as the smallest response unit (Agarwal et al. 2002). Modelling approaches follow either a bottom-up or a top-down approach, i.e. land use changes are observed at the regional scale due to exogenous drivers, or pre-defined regional targets for land use change are assigned to individual response units,

e.g. a certain level of food production (Verburg 2006). In this context, spatially explicit geospatial land use models can be distinguished from other agro-economic models such as farm models, e.g. EFEM or agricultural sector models, e.g. CAPRI.

An example of a spatially explicit agro-economic supply model is *PALUD* (Parcel based Agronomic Land Use Decision model). It is a geospatial economic land use model based on linear programming and written in GAMS (Sponagel et al. 2022). The model requires various data such as land use, e.g., based on the Integrated Administration and Control System or high-resolution remote sensing data (e.g. Blickensdörfer et al. 2022). The objective function optimizes land use by maximizing the gross margin across all land units (usually cropland and/or grassland, depending on the research question) in the study area. The optimization is subject to various constraints, such as agronomic or labour constraints. The model does not represent individual farms (see e.g. EFEM) as it follows a "region farm" approach. This means that a municipality or district (depending on data availability) is considered as a farm with its specific constraints at the farm level, such as livestock feed demand, labour constraints or marketing constraints (e.g. for root crops). However, livestock farming is typically integrated in a rather simplified way. This can include meeting specified feed requirements based on observed livestock numbers and standard assumptions about feed rations.

PALUD is particularly useful for answering biodiversity questions because it allows the spatial effect of landscape elements such as hedges or semi-natural habitats such as flower strips to be taken into account (Sponagel et al. 2025). Another strength is the analysis of spatially explicit land-use competition for food production, renewable energy, but also for settlement and infrastructure (Sponagel et al. 2024).

2. ***Examples of Techno-Economic Optimization Models for Biomass Supply Chains***
   Biorefineries or bioenergy production plants often present two challenges that are difficult to combine in models. On the one hand, they require a certain plant size to be economically viable. On the other hand, larger plants require a significant feedstock and associated supply area. Logistics costs often play an important role in the economics of such plants. For this reason, optimization models have been developed in recent years to determine possible locations for bioenergy combustion plants or biorefineries. Two such models are presented below.

   BeWhere is a spatially explicit techno-economic engineering model for the optimization of renewable energy systems. It is a mixed-linear programming model and is used at the International Institute for Applied Systems Analysis (IIASA) to evaluate the location, size and technology of the renewable energy system. It can be applied at local, regional, national or EU level. In the area of biomass for energy, BeWhere minimizes the costs of the entire bioenergy supply chain, including biomass harvesting and transport, biofuel conversion, transport, and delivery, and heat and electricity sales. A wide variety of feedstocks can be considered in the model. However, the focus is on second-generation biofuels and therefore crop residues, forest residues and lignocellulosic industrial waste are included in the model (Wetterlund et al. 2013). New applications are the production of renewable marine fuels for decarbonized shipping (Harahap et al. 2023) or the spatially and temporally disaggregated analysis of intensive palm oil-based bioenergy use

(Mohd Idris et al. 2021). More information can be found ▶ here.

BiOLoCaTe (Biomass value chain integrated Optimization for Location, Capacity and Technology planning) is also a mixed-linear programming model used to optimize biomass supply chains. This techno-economic assessment includes supply, logistics and conversion processes and is carried out on the basis of achievable profit, which is the result of revenue generated from the sale of either electricity and thermal energy or bio-based materials. The model results can be used to support decisions in regional planning of biomass-based value chains (Rudi et al. 2017). Compared to BeWhere, it is not only used to evaluate renewable energy systems but also bio-based material production systems. It is currently only applied in Baden-Württemberg (a state in south-western Germany) but can be adapted to other regions or countries.

The energy sector is generally integrated either through CGE or PE models. An example of a disaggregated, bottom-up model is TIMES PanEU (Pan-European TIMES model). It has been used in several analyses of the European energy system. The model minimizes an objective function by representing the total discounted system costs from 2010 to 2050 and assumes perfect competition between different technologies and paths of energy conversion and supply. It is a multi-regional model covering all sectors related to energy supply and demand at the country level. TIMES PanEU covers all EU28 countries as well as Switzerland and Norway. In addition, both GHG emissions and pollutant emissions are included in the model by including process-specific emissions.

The model is flexible in terms of regionalization (e.g. within Germany) and both energy and non-energy options for the use of bioenergy in the energy system or modelled technology pathways. When using the model, a detailed analysis of the competition between alternative technologies and the energy use of biomass pathways can be taken into account for the overall economic perspective, thus making the contribution of biomass to the achievement of policy goals available (Blesl et al. 2012; Deppermann et al. 2016).

42.2.2 Agent-Based Models

Agent-based models (ABM) are a type of bottom-up model: They simulate higher- level variables of interest (e.g. commodity supply, land use patterns, regional economic development, food security or structural change in agricultural sectors) as emergent phenomena by explicitly modelling the behaviour of individual actors, the agents. The direct modelling of decision-making entities and their interactions, rather than relationships between aggregate variables, is its key feature (Pyka et al. 2022).

There is a wide variety of ABM applications. Here, we briefly introduce three main strands of the literature that may be relevant to bioeconomy-related research: The first strand is strongly inspired by early ABM in biology, which showed that complex collective behaviour, such as the movement of a swarm of fish or a flock of birds, can be explained by very simple rules for individual members of the swarm or flock. These rules typically focus on the adaptation of one's own behaviour to that of neighbours in the swarm or flock, resulting in collective behaviour of the aggregate that follows purely from simple rules for the individuals. Bioeconomic models in this tradition focus on the interaction between agents and often explicitly discuss evolutionary components, i.e. survival of economic agents or economic strategies. The behaviour of individual agents typically follows simple heuristic rules and sometimes behavioural patterns derived from evolutionary strategies (imitation of peers, repetition of previous behaviour, experimentation and search for new strategies, see e.g. Gotts and Polhill (2009)).

The second strand consists of individual-based models in ecology. In this type of model,

the agents are individual animals that exhibit species-specific characteristics and behaviour. Interacting with other individuals of the same or different species in a landscape, population dynamics, predator–prey relationships and biodiversity emerge as aggregate variables of interest (see e.g. Grimm et al. 2017; Romero-Mujalli et al. 2019).

The third strand of literature develops ABMs starting from microeconomic bottom-up models, such as representative farm models or microsimulation models: The behaviour of individual agents is typically based on established microeconomic approaches, such as mathematical programming models, to capture complex farming decisions. This basic approach is then transformed into an ABM by extending it in (up to) four dimensions: agent heterogeneity, dynamics, behavioural complexity and interactions (Berger and Troost 2014; Mössinger et al. 2022).

Heterogeneity refers, on the one hand, to the possibility of including different types of agents (e.g. farms, traders, cooperatives, processing plants, water user associations, etc.), which allows, for example, the simulation of supply chain relationships. On the other hand, it also refers to an improved representation of heterogeneity among individuals of the same agent type. These models are typically not limited to a few representative agents but include an agent for each relevant actor (e.g. farm) in a study area, or at least a number large enough to represent the full statistical heterogeneity of the real-world population and allow meaningful simulation of interactions. This allows, for example, an in-depth analysis of the distributional consequences of policies: Are they more likely to affect poorer or richer households, larger or smaller farms, diversified or specialized firms, upstream or downstream water users?

Dynamic components included in such an ABM can be, for example, crop growth or agro-ecology models to simulate short and long-term consequences of land use choices (yields, soil erosion, water pollution), hydrological models to simulate water supply for irrigation, market models (including land markets) to simulate economic consequences, communication and innovation diffusion models to simulate the spread of new technologies. A key feature of ABM is that there is dynamic feedback between agent decisions and processes in the biophysical or socio-economic environment. Agents do not make a decision once and for all, but do so repeatedly at different times in response to developments in their environment, which may be caused by external factors (such as the weather or world markets) or may be consequence of their own or other agents' actions.

Interactions between agents typically arise through such dynamic model components: Agents' land use may affect neighbouring agents through erosion, changes in water balance and flows, or pollination services. Supply and demand in markets change prices and affect opportunities for economic expansion. Technology investment by one agent may encourage other agents to follow suit, reducing information and adoption costs and increasing confidence in the technology. In addition, interaction and collective action can be explicitly incorporated by including models of cooperatives, auctions and, of course, trading relationships between different actors in the supply chain.

In addition to dynamics external to the agent, internal agent dynamics such as observation, information processing or learning can be added, allowing the simulation of *complex behaviour* that goes well beyond omniscient profit maximization. Schlüter et al. (2017) discuss how a combination of different components can be used to implement a variety of theories of human behaviour.

It should be emphasized, that a typical ABM will not use all of these features at once, but only a selected combination. On the contrary, a key principle of simulation analysis is to match the complexity of the model to the modelling task, i.e. to include only those model features that are relevant to the research question. ("As simple as possible, as complex as necessary.")

Using targeted combinations of these features, ABM has been successfully used, for example, to analyse structural change in the agricultural sector in response to policy (e.g. Appel and Balmann 2023; Berger 2001; Happe et al. 2008), to understand farmers' responses,

adaptation options and distributional consequences to climate change effects and mitigation policies (Berger et al. 2017; Carauta et al. 2021; Kreft et al. 2024; Troost et al. 2015), the life-cycle assessment of biomass production (López i Losada et al. 2024), the design of circular strategies in local agricultural systems (Fernandez-Mena et al. 2020) or the optimal location of a biorefinery (Zupko 2021).

42.2.3 Environmental and Biophysical Models

The transition from a petroleum-based to a bio-based economy will inevitably lead to increased demand for agricultural and forestry biomass. This increase in biomass production, both regionally and globally, may in turn lead to increased conflicts of interest with environmental protection and nature conservation. It is therefore necessary to consider not only the economic aspects but also the environmental impacts of a developing bio-economy. As agricultural and forestry production is systematically linked to the use of natural resources, many models have been developed in recent decades to simulate these environmental impacts.

Biophysical models are process-based models that represent biological, geological, and chemical processes in environmental systems. They include, but are not limited to, crop growth and soil physical models. Some models also examine a wide range of environmental impacts of agricultural and forestry management systems. In addition, there are a variety of models that examine different scales from plot to farm, region and global scales. Some models were originally developed and validated for smaller area units, but due to increased demand for agricultural and environmental policy assessment, they have been further developed for regional and global scales. In the early 2000s, considerable political and scientific focus was placed on the assessment of agricultural GHG emissions, resulting in a large number of economic models being combined with biophysical models at a regional level. In particular, soil GHG emissions could be clearly identified and the costs of mitigation options assessed. For example, the CAPRI and EFEM models mentioned above have been linked to the biophysical models DNDC (DeNitrification-DeComposition) and EPIC (Environmental Policy and Integrated Climate) (Neufeldt et al. 2006; Schwarz-v. Raumer et al. 2017). EPIC is also integrated into several Integrated Assessment Models (Kraxner et al. 2013; Zessner et al. 2017) and is described below as an example of the functions of biophysical models.

Ecosystem models also play an important role in analysing the effects of climate change on biomass production. Extreme weather events such as heat waves and droughts, but also heavy precipitation events, play an important role. It is also important to identify measures to make agriculture and forestry more resilient.

■ Examples of environmental and biophysical models

EPIC (Environmental Policy and Integrated Climate) was originally developed at the United States Department of Agriculture to study the effects of agricultural production on erosion and soil productivity. Since its inception, it has been developed by several research institutes into a comprehensive terrestrial ecosystem model that simulates a wide range of ecosystem processes and can take into account a wide range of land use management options (e.g. tillage, harvest, fertilization, irrigation, drainage, liming, burning and pesticide application). The main components, among other, in EPIC are crop growth, weather simulation, hydrology, nutrient and carbon cycling, soil temperature and moisture, soil erosion and soil management (Izaurralde et al. 2012). When combined with economic models or model networks to assess biomass production in agriculture and forestry, EPIC can be used to address two important research questions: the impact of changing environmental conditions on biomass production, e.g. such as projected crop yields affected by climate change (Zilli et al. 2020), and the environmental impact of different management options for

biomass production on the environment, such as erosion, nitrogen leaching, or soil-borne greenhouse gas emissions (Schwarz-v. Raumer et al. 2017). EPIC can also be applied at a global scale. For example, Carr et al. (2021) examined global crop losses of maize and wheat due to water erosion. They found that the areas most affected by water erosion are outside the main maize and wheat growing areas. This means that overall global losses are comparatively small. But it also shows that the most climate-vulnerable areas, such as sub-Saharan Africa and regions of Central and South America, are hardest hit.

Another widely used crop growth model is *CERES* (Crop Environment Resource Synthesis). This model has been developed and used over the last 30 years to simulate crop growth and nutrient balances in response to climate, soil, genotypes and management at different locations around the world. Many model variants of CERES have been developed. For example, *CERES-EGC*, which has been developed by the French research institute INRAE (Institut national de recherche pour l'agriculture, l'alimentation et l'environnement) to include functions for determining soil-borne greenhouse gas emissions and a differentiated soil organic carbon budget. It is linked to economic models and life cycle assessments to evaluate the environmental impact of agricultural production (e.g. El Akkari 2023).

CERES is also integrated as a crop growth sub-model in the widely used *DSSAT* (Decision Support System for Agrotechnology Transfer). DSSAT can be used to address a wide range of issues at different spatial and temporal scales. These include comparing different management options, regional assessments of the effects of climate variability and change, the impact of irrigation on yields, greenhouse gas emissions and long-term sustainability through soil carbon and nitrogen balances. DSSAT is used by more than 25,000 researchers, educators, consultants, agricultural advisers, farmers and policy makers in more than 187 countries worldwide. More information can be found ► here.

LPJmL (Lund-Potsdam-Jena managed Land) is an example of a Dynamic Global Vegetation Model (DGVM) designed to simulate the global terrestrial carbon cycle and the response of carbon and vegetation patterns to climate change. It was developed by a consortium of scientists from the Max Planck Institute for Biogeochemistry in Jena, the Potsdam Institute for Climate Impact Research, and Lund University. To study the role of the biosphere in the anthroposphere, it is crucial to represent both natural and agricultural ecosystems in a single, internally consistent modelling framework. The model is designed to simulate the composition and distribution of vegetation as well as the stocks and fluxes of carbon and water between land and atmosphere for both natural and agricultural ecosystems. Using a combination of plant physiological relationships, generalized empirically established functions and plant trait parameters, the model simulates processes such as photosynthesis, plant growth, maintenance and regeneration losses, fire disturbance, soil moisture, runoff, evapotranspiration, irrigation and vegetation structure. As a result, the model facilitates the integration of agricultural systems into the global climate-vegetation system (Bondeau et al. 2007). Within the PIK model network, LPJmL is linked to MAgPIE (Model of Agricultural Production and its Impact on the Environment) and REMIND, a global multi-regional model including the economy, the climate system and a detailed energy sector. More information can be found ► here.

42.2.4 Integrated Assessment Models

The idea of Integrated Assessment Models (IAMs) is to design and assess interactions between human activities and the natural environment. For this purpose, models representing either anthropogenic or (bio-)physical systems, are coupled. Integration can refer to the analysis of coherent problems and the integration of stakeholders, disciplines, processes,

and models at both temporal and spatial scales. This can be done in interdisciplinary and integrated approaches as stand-alone models, or in a framework of multiple, coupled models focusing on different issues or scales originating from different disciplines (Wicke et al. 2015). All of the models described above can be part of such a modelling collaboration.

> ***Integrated assessment models*** describe and assess the interactions between human activities and (global) environmental processes. They include models of socio-economic systems, environmental systems and the interactions between the two.

The main advantage of IAMs is that they overcome the limitations of models that focus on specific issues, e.g. agriculture or energy, without considering the impacts of human activities on (bio-)physical systems. By coupling different models, IAMs can cover a range of different disciplines and research fields, including economics, energy analysis, agricultural analysis and biophysical sciences, thus bridging the economic, social and environmental dimensions of bio-economic developments. In the context of a bioeconomy, IAMs could elucidate in an integrated way the impacts on energy systems as well as on natural systems such as land and water use, and interactions with global cycles such as carbon.

Models can be linked in several ways to achieve an integrated assessment (Wicke et al. 2015):

- Align and harmonise input data for the different models and levels of aggregation, e.g. the number of economic sectors and scenario definitions.
- Align and harmonise key assumptions: if this is not possible, at least a systematic comparison of results and sensitivities should be carried out to highlight differences between models.
- Link models: integrate model ranges by using results from one model as inputs to another (one-way data exchange), or iterate inputs (two-way data exchange) through partial integration via a simplified version of one model in another model, or full integration by solving models simultaneously.

An alternative distinction in model coupling is often made between soft links, where models are linked exogenously by transferring the results of model runs from one model to another, and hard links, where models exchange information directly and are solved iteratively so that the solutions are internally consistent between models. Soft links allow more components to be included, but require careful coordination of data flows to avoid unnoticed inconsistencies between models. In contrast, hard links allow for more consistent representation of the systems, yet increase complexity and reduce transparency (Leimbach et al. 2011).

The Integrated Assessment Modelling Consortium (IAMC) was established in 2007. It is an organisation of scientific research institutions engaged in integrated assessment modelling and analysis. The IAMC has members from all over the world, operating most of the IAM models currently in use. The IMAC wiki is an excellent source of information about IAMs, providing model documentation for participating models and model networks. More information can be found ▶ here.

IMAGE from the Netherlands Environmental Assessment Agency (PBL), is a well-known IAM. It identifies socio-economic development pathways and predicts their impacts on energy, land, water and other natural resources. It also takes into account unintended side effects such as emissions to air, water and soil, climate change, and the depletion and degradation of remaining stocks (fossil fuels, forests). One example of the many applications is the study by Gernaat et al. (2021) which examines the impacts of future climate change on global renewable energy production.

42.3 Scenarios: Revealing the Trails Into the Future

A key feature of models is their predictive ability to explore future developments based on specific conditions or interventions. To accomplish this predictive task, models are only part of the story; the other part is *scenario analysis*, a key tool of bioeconomy modelling. It allows scientists to explore different futures under different assumptions, such as changes in consumer behaviour or technological advances in bio-based industries. By evaluating potential scenarios, such as increased demand for biomass or changes in carbon taxes, models enable decision-makers to consider both the opportunities and trade-offs in the bioeconomy transition.

42.3.1 Why Do We Need Scenarios?

One of the main goals of modelling is to generate system knowledge. This means providing a deeper insight into a system in order to better understand its interrelationships. Alternative development trends and environmental conditions can be presented, evaluated and categorized in terms of their consequences. In the case of the bio-economy, for example, the question can be asked how the expansion of certain bio-economy crops will affect other environmental goods—are there trade-offs or perhaps even synergies? The use of modelling can thus significantly support policy making, for example in the implementation of the Common Agricultural Policy. This is because different possible future states can be analysed and then assessed to determine the extent to which they correspond to a desired target state.

From a modelling perspective, this means analysing different scenarios. These scenarios must first be developed and serve as plausible, simplified, alternative visions of the future. These future scenarios are subject to certain assumptions about the key driving forces in the system and their interactions, such as the evolution of legal, political and technological frameworks (Millennium Ecosystem Assessment 2005). Scenarios are therefore always conditional on the assumptions made. In addition, they are always potentially possible future states, although no statements can be made about the probability of their occurrence (Van Vuuren et al. 2012).

As quantitative modelling is often time-consuming, only a limited number of model runs can usually be performed. This may limit the number of scenarios that can be considered. Scenario development prior to quantitative modelling is therefore an important step in the research process. For example, scenario development can be used to identify knowledge gaps in a system or to derive hypotheses. This is particularly the case when there is still little empirical knowledge in an area, which is very likely to be the case when innovations or transitions are introduced. There is also a close link with the bio-economy, for example when it comes to establishing new value chains, such as packaging materials made from bio-based raw materials such as silphia. Possible knowledge gaps could relate, for example, to the impact on agricultural cropping patterns and biodiversity. This question could then be specifically analysed with the help of a model. In this context, scenarios can also provide important information on the framework conditions, i.e. what will be the size of the paper industry's demand for biomass or what could be the range of market prices? A model can then be used to derive possible supply functions on the part of agriculture, for example.

42.3.2 How Can Scenarios Be Categorized?

Depending on their purpose, scenarios can be categorized in different ways. In this context, Börjeson et al. (2006) divide scenarios into three different categories:

- Predictive
- Explorative
- Normative

Predictive scenarios are used to answer the question of what is likely to happen in the

future under certain circumstances. This can be either in the form of an outlook, i.e. a kind of extrapolation of current developments, or in the form of what-if scenarios in the context of more disruptive events. These are individual events, such as policy decisions regarding the promotion of renewable energy. For example, one might ask what would happen if a particular subsidy were removed.

Explorative scenarios are more concerned with what might happen in the future. While what-if scenarios tend to look at today's perspective or the near future, the time reference for explorative scenarios tends to be in the more distant future. This means that fundamental changes can be considered, such as changes in social values and consumer habits. Often, not just one scenario is considered, but a number of different scenarios that reflect a wider range of possible developments. For example, it is quite conceivable that the provision of larger amounts of biomass to the bioeconomy could be assessed differently in terms of its impact on biodiversity, depending on the external conditions of the scenario. With otherwise unchanged domestic demand for agricultural products, or perhaps increasing global demand for agricultural products with corresponding price signals on the world market, competition for land use could potentially increase significantly. Under different framework conditions, such as a sharp reduction in meat consumption or innovations in protein production, the expansion of biomass supply for the bioeconomy is likely to be assessed quite differently in terms of biodiversity impacts. Particularly in the context of explorative and future-oriented studies, this example illustrates the high relevance of considering the external framework conditions in a system under consideration, which can be systematically constructed with the help of scenarios. A distinction can also be made between external and strategic exploratory scenarios. External scenarios take into account factors that cannot be directly influenced by stakeholders. For example, if stakeholders at the regional level are developing concepts for the expansion of the bioeconomy, developments in the global agricultural market are not within the sphere of influence of these actors. However, they are relevant to considerations at the regional and local level. From the point of view of the actors, the aim would be to develop strategies that are as robust as possible, i.e. strategies that will lead to the desired success even in the context of different external scenarios. Strategic exploratory scenarios focus on these strategies in relation to internal drivers, such as the implementation of certain policies, taking into account overarching or external developments. Usually, a target variable is defined to evaluate the strategies, e.g. the share of bio-based raw materials in industry in the context of an expansion of the bio-economy. An example of a set of exploratory scenarios is given in ◘ Table 42.1. The explorative scenarios presented here aim to explore the potential future impact of the bioeconomy on agriculture in the German state of Baden-Württemberg. In order to reflect a wide range of future developments, the scenarios differ, for example, in their underlying assumptions about the amount of biomass used for innovative chemical and material applications. In addition, nutritional trends were considered in one of the scenarios.

In contrast to the other two types, normative scenarios are concerned with how to achieve a pre-defined goal. In the context of economics, the focus is often on cost efficiency, i.e. how to achieve a defined goal at the lowest possible cost. However, multiple objectives may be defined in different areas, such as achieving certain environmental objectives while providing a certain amount of biomass for material use. Normative scenarios can be of a more conservative or transformative nature. The former focuses on short-term optimization within the existing framework of a system, while the latter focuses on a more long-term and fundamental change of the system.

In addition to the categories of scenarios described above, scenarios can also be divided into qualitative and quantitative scenarios. In contrast to quantitative scenarios

Table 42.1 Example of a set of explorative scenarios for modelling the future of bioeconomy with an economic farm model in 2050 (Petig et al. 2019)

Scenario	Share of renewables in electricity generation	Annual change of biomass in innovative chemical and material use	Dietary trends
Business-as-usual	80% in 2050	No change	No change
Expansion of innovative material use	80% in 2050	5.5%	No change
Expansion of traditional and innovative material use	80% in 2050	8.1%	No change
Expansion of traditional and innovative material use with more sustainable food consumption	80% in 2050	8.1%	Cereals, sugar, potato, eggs, plant oils (−10%), meat products (−41.1%), dairy products (−29.7%)

that are usually the result of a simulation model, qualitative scenarios are not based on concrete numerical data, but rather on narratives or storylines. They can integrate the perspectives of different stakeholders from different disciplines and sectors and have a strong communicative character. However, some of these storylines can also be supported by specific quantitative data and can then be used as a starting point for quantitative modelling. This is a story and simulation (SAS) approach. This shows that the transitions between qualitative and quantitative scenarios can also be fluid (Alcamo 2008a, b; Kosow and Gaßner 2008).

In the past, the SAS approach has sometimes been criticised for the fact that the development of scenarios is often very simplified compared to quantitative modelling and therefore does not do justice to the underlying complexity (Garb et al. 2008). Disadvantages have been identified, for example, in the transparency and hence reproducibility of qualitative scenarios (Alcamo 2008a, b). To address these challenges, more formalized methods can also be used in scientific practice, which allow the systematic and reproducible generation of qualitative scenarios. One example is cross-impact balance analysis (Weimer-Jehle 2006), which will be discussed in more detail below.

42.3.3 Approaches for Scenario Development

There are various approaches to scenario development that allow for the integration of relevant stakeholders. In this section, a selection of approaches is presented and discussed.

Delphi Approach

Delphi surveys follow a structured and iterative process. A Delphi survey, therefore, consists of at least two rounds. In the first round, the opinions of invited experts are collected. In the second round, the experts are also confronted with the assessments of their peers. The assumption here is that the assessment of other experts also influences their own perception. Ideally, after several rounds, there will be an increasing convergence of expert opinions, so that the most relevant pathways or scenarios can be derived. The method can, therefore, be used to derive a kind of consensus among experts or to generate a range of potential future options, which is usually the aim in the context of explorative scenarios (Turoff 1970).

An example of the Delphi approach can be found in Hurmekoski et al. (2019) who developed future scenarios for the European forest-based bioeconomy in 2030. They followed a three-round Delphi approach. In the first round, semi-structured telephone inter-

views were conducted to explore all possible factors relevant to the research objective. For this purpose, 41 experts from academia, industry, NGOs and other sectors were identified. As a result, 40 statements were formalized and presented in a second-round online survey where the experts were asked to indicate to what extent they agreed with each statement. For example, "EU bioenergy markets will keep growing roughly in line with the trends of the past decade".

For the third round, seven statements were selected, which were characterized by the highest level of conflicting assessments. Here, too, the opinions of others were presented to see whether experts would change their own opinions, leading to a higher level of consensus.

As a result, it was possible to identify potential future developments for which there was a broad consensus, for example that the demand for wood will increase significantly by 2030. These results can also be highly informative for any modelling studies on the future of the bio-economy, as they allow for the definition of general framework conditions.

Cross-Impact-Balance Analysis

The Cross-Impact-Balance (CIB) analysis is a structured qualitative method to derive future scenarios based on expert assessments (Weimer-Jehle 2006, 2023a). The CIB, thus, represents a system such as the agri-food system with its most relevant descriptors and their interrelationships. With the CIB method, it is, therefore, possible to gain insights into complex systems and to generate relevant system knowledge. This is particularly important for research areas where, for example, appropriate data are not yet available for any kind of quantitative modelling. In this respect, CIB can also do some of the groundwork for more focused modelling, for example by showing where the most important knowledge gaps are (Kosow and Gassner 2008; Weimer-Jehle 2006). The CIB context scenarios can then provide input to quantitative models (Prehofer et al. 2021).

The CIB method can be applied in four steps, for example (see Fig. 42.5). The first step is to derive the descriptors of the system, which can be based, for example, on literature or expert interviews. The second step is to define trend alternatives, i.e. how certain descriptors might develop in the future. For example, the demand for bio-based materials could remain at the current level or increase by about 50%. In the third step, the interaction between the previously defined descriptors and their respective trend alternatives is assessed on a semi-quantitative scale (e.g. –3 for a strongly inhibiting effect or +3 for a very favourable effect). This can be done by inviting experts. In general, there are many ways to carry out this assessment, e.g. the experts can assess the interactions individually and average them, or the values can be defined in a more open discussion. When selecting descriptors, it should be borne in mind that the number of interactions can be quite high as the number of descriptors and trend alternatives increases. For reasons of practicality when working with expert groups and their potential time constraints, the method is more appropri-

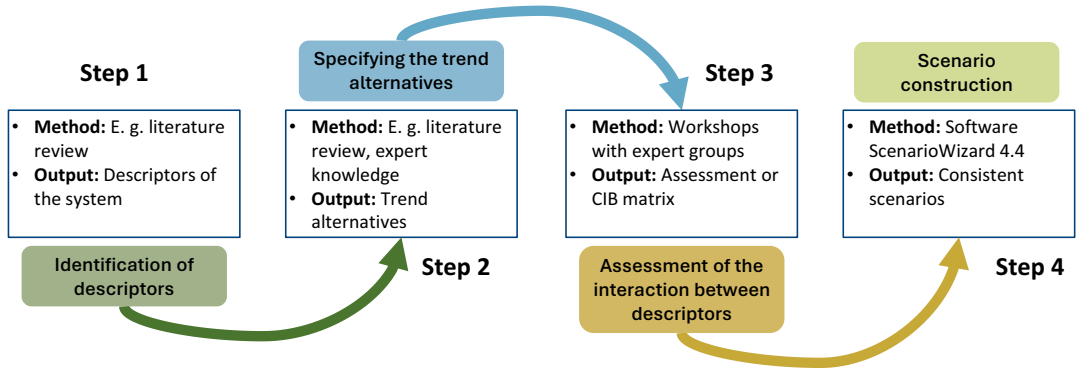


Fig. 42.5 Overview of the Cross-Impact-Balance analysis approach (Based on Sponagel et al. 2025)

ate for systems with a moderate number of descriptors. It should also be noted that expert judgements can also be subject to uncertainty (Weimer-Jehle 2006). Finally, consistent scenarios are derived by calculating a cross-impact balance using the "ScenarioWizzard" software (Weimer-Jehle 2023b). More detailed information on the methodological approach can be found in Weimer-Jehle (2023a).

In the project "German Biodiversity Assessment" (Sponagel et al. 2025, Wirth et al. 2024), the CIB method was applied to agri-food systems with the aim of deriving scenarios that lead to an increase in biodiversity in German agricultural landscapes. Following the above approach, a total of eight descriptors were defined based on expert knowledge and literature (see Fig. 42.6). They represent the most important indirect drivers of biodiversity in agricultural landscapes. They include, for example, the demand for agricultural goods from a global perspective or the development of the Common Agricultural Policy (CAP) in the European Union. The development of biodiversity in agricultural landscapes was treated as the dependent variable. At this point, the advantage of CIB is that it can be used to derive scenarios that are consistent in themselves. This means that the question always arises as to which combinations of trend age alternatives of the individual descriptors can be consistent at all. For example, a strong global increase in demand for agricultural commodities and the focus of the Common Agricultural Policy on environmental services were considered to have a rather inhibiting influence due to potential incentives for intensification resulting from price signals on the world market.

This means that it does not affect the other descriptors, but biodiversity is affected by them. Finally, it was possible to filter out scenarios that only included improvements in biodiversity. The assessment of interactions between trend alternatives was carried out in three workshops with three different groups of a maximum of eight experts from different sectors and disciplines, such as agricultural economics or landscape ecology, lasting about 3–4 hours. The idea behind this approach was to generate more robust scenarios. In the end, the focus was on scenarios identified independently within each expert group. For example, one of the final scenarios for improving biodiversity included a shift in the CAP towards environmental performance and innovation in

Descriptor	Trend alternatives	Descriptor	Trend alternatives
A. Land use pressures	A1 Strong increase in land use pressures	E. Societal values	E1 Sustainability and post-materialism
	A2 Moderately sustained land use pressures (BAU)		E2 Continuation of social complexity (BAU)
	A3 Decrease in land use pressures		E3 Dominance of materialism
B. Demand for agricultural goods	B1 Stable supply situation	F. Biodiversity in agricultural landscapes	F1 Improvement
	B2 Thünen Baseline 2032 (BAU)		F2 Constant (BAU)
	B3 Global food crisis		F3 Deterioration
C. Common Agricultural Policy	C1 Loss of importance of the CAP	G. Role of agriculture	G1 Extensification and public goods
	C2 Update of the current CAP (BAU)		G2 Business-as-usual (BAU)
	C3 Focus on environmental performance		G3 Intensification of production
D. Nature conservation policy and law	D1 Strong legal tightening	H. Technological and economic developments "shocks"	H1 Innovations in plant production
	D2 Moderate legal tightening (BAU)		H2 Innovations in protein production
	D3 Market-oriented nature conservation		H3 National economic slump
	D4 Withdrawal of the state from nature conservation policy		H4 Global recession

Fig. 42.6 Overview of descriptors that have defined within a CIB scenario analyses in the project "Faktencheck Artenvielfalt". (Based on Wirth et al. 2024)

protein production, while societal values remain unchanged and we face a stable supply situation. This biodiversity enhancement scenario framework could now be used, for example, as input for quantitative modelling.

42.4 Data Sources for Modelling the Bioeconomy

Earlier in this chapter, it was stated that modelling can "transform vast amounts of data into actionable insights". While *data drives decisions, only accurate data drives good decisions*. This means that a model is only as good as the data that feeds it, as the saying goes: "Garbage in, garbage out!" This subsection provides a brief overview of some commonly used data sources for bioeconomy modelling. These include national data sources with examples from Germany, as well as European and global data sources. A more detailed overview is provided in Supplementary material 42.1.

The *Farm Accountancy Data Network (FADN)*, is a European Union system for collecting and analysing economic data from agricultural holdings to support the Common Agricultural Policy (CAP). It is managed by the European Commission and covers agricultural holdings in all Member States, subdivided into regions (e.g. NUTS-1 and NUTS-2 levels). Each year, data are collected from a representative sample of farms—including production yields, costs, profits and market prices—allowing profitability assessments and economic comparisons between regions and farm types. FADN also underpins agricultural economic modelling and policy evaluation. The publicly available FADN will transition to the Farm Sustainability Data Network (FSDN) in 2025, which will include environmental and social sustainability metrics.

Standard calculation data quantifies the costs and revenues of agricultural production methods, helping farmers and advisors to assess profitability and efficiency. These calculations include revenues (e.g. product prices) and detailed costs, including variable (e.g. seeds, feed, labour) and fixed (e.g. machinery) costs. Key metrics such as gross margin (revenue minus variable costs) inform business planning, investment decisions and comparisons of farm efficiency. Such data are widely available at national (e.g. KTBL in Germany) and EU level, with datasets derived from FADN records.

Land use data are crucial for agricultural optimization modelling. They require high spatial resolution to accurately reflect local conditions. Sources include official statistics, remote sensing and the Integrated Administration and Control System (IACS), which tracks land use at parcel level for CAP interventions. IACS provides annual updates on crop types, biodiversity measures and management intensity, supporting policy assessments such as the Green Deal and geospatial modelling (European Commission 2024).

Statistical databases compile data for research and policymaking in various fields. For example, FAOSTAT provides global agricultural data (e.g. production, trade, emissions), EUROSTAT provides EU-wide statistics on the economy, demography and energy. For Germany, DESTATIS contains national data on socio-economic and environmental indicators, and at the level of the federal states, there are usually also statistical offices that provide region-specific data, such as StalaBW for Baden-Württemberg, Germany.

Emissions inventories track greenhouse gas emissions for the national reporting. Agricultural inventories include methane from livestock, nitrous oxide from fertilizers and carbon dioxide from land-use changes. These rely on national statistics and standardized emission factors for accuracy (Vos et al. 2022).

42.5 How to Use Modelling in the Bioeconomy

Models play an indispensable role in shaping the bioeconomy, providing tools for understanding complex systems, guiding decisions and predicting outcomes. They help to optimize resource use, minimize environmental impacts and explore scenarios for sustainable growth. However, their use must be approached with caution and responsibility and with awareness of the limitations of individual models.

Excursus 42.2. All Models are Wrong

"All models are wrong [, but some are useful].", a statement coined by George Box (1976; Skogen et al. 2021), emphasizes that models simplify the real world and are therefore *wrong* in the sense that a 100% reproduction of the real world would be *right*. Simplification is done for technical and practical reasons and is best illustrated by an example:

A map is a model of the real world. It does not show all the details of the real world, for example forests are only dark green and you cannot see every single tree. So, maps are wrong!—But they are useful because they can help you find your way. A more detailed map showing every single tree is not necessary to fulfil the purpose of a map as an orientation guide.

So, when making models, it is important to consider what detail is important to fulfil the purpose of the model and what can be simplified or neglected.

Bio-economic models, like any other, have inherent limitations due to assumptions, simplifications and uncertainties in their design. Overconfidence in their results risks misguiding policy and undermining public trust. Decision-makers need to recognize that models are tools for exploration rather than definitive answers, and should use them as part of broader, deliberative processes that include diverse perspectives and acknowledge uncertainties. To ensure that models truly benefit the bioeconomy, they must be transparent, sensitive to the social context, and subject to robust validation and sensitivity analysis. Engaging stakeholders throughout the model lifecycle, openly communicating limitations, and resisting the allure of excessive complexity are essential practices (Saltelli et al. 2019, 2020).

In the bioeconomy, where the stakes are high and systems are complex, the value of modelling lies in its ability to enrich understanding, foster dialogue, and support informed decision-making. By adhering to best practices, we can ensure that models serve society and promote the sustainable and equitable development of the bioeconomy.

Questions

1. Explain the difference between model verification and model validation.
2. Give two examples of bottom-up and top-down models and explain the differences.
3. How can scenarios be categorised?
4. Describe the meaning of the phrase: "All models are wrong, but some are useful."?

Answers

1. Verification addresses the question "Did we build the model right?" and focuses on the correct implementation and technical/mathematical correctness of the model. Validation addresses the question "Did we build the right model?" and assesses if the model can adequately support the intended use.
2. Bottom-up models start from individual components to build up an understanding of the whole system. Examples include agent-based models and biophysical models (e.g. CERES). Top-down models analyse systems at a macro level, such as macroeconomic models that simulate trade (GTAP), sectoral models such as GLOBIOM. Bottom-up models prioritize detailed, localized processes, while top-down models emphasize large-scale dynamics using aggregated data.
3. Scenarios can be categorized into three types: Predictive, Explorative, and Normative. Predictive scenarios forecast likely outcomes by extrapolating current trends and data. Explorative scenarios examine a range of plausible futures, focusing on uncertainties and "what-if"

situations. Normative scenarios envision a desired future and outline steps to achieve it.

4. The phrase means that models are simplifications of reality and cannot perfectly represent complex systems, so they are inherently flawed. However, they can still provide valuable insights and guide decisions when used with an understanding of their limitations and context. The phrase emphasizes the importance of critical evaluation and appropriate use of models.

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Bioeconomy Monitoring

Andrea Camia

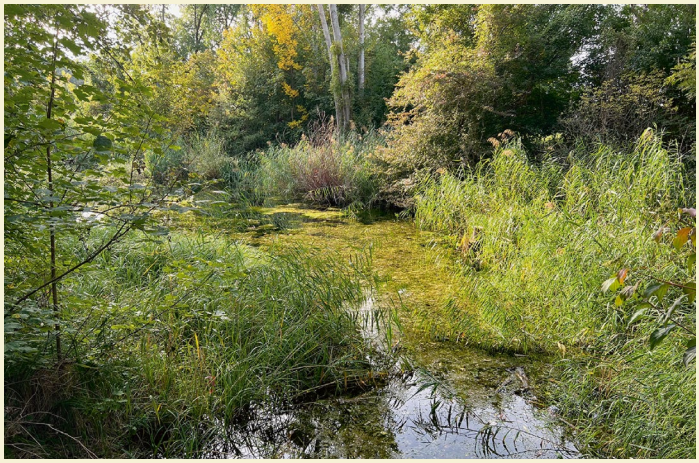


Fig. 43.0 Bioeconomy monitoring. © Andrea Camia (► https://doi.org/10.1007/000-hvr)

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Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/978-3-032-09098-0_43. The videos can be accessed individually by clicking the DOI link in the accompanying figure caption or by scanning this link with the SN More Media App.

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Bioeconomy monitoring tracks the progress of bioeconomy towards its strategic objectives, enabling informed decision-making and timely adjustments. A Bioeconomy Monitoring System (BMS) is vital for assessing the environmental, economic and social impacts of bioeconomy, addressing its complexity and potential trade-offs. The system must be well-structured, covering all dimensions of sustainability, and provide reliable information across sectors and across the territory at different scales. Essential components of a BMS include a data collection and storage infrastructure, methods and tools for data processing and evaluation and tools for regular reporting and dissemination. The design and implementation of a BMS involve three key stages: conceptualisation, where the scope and framework are defined; implementation, focusing on indicator selection and data processing; assessment and communication, evaluating trends and communicating results. The EU Bioeconomy Monitoring System was developed to track progress towards the EU Bioeconomy Strategy's objectives. This system, managed by the Joint Research Centre (JRC), relies on existing data sources to ensure consistency with international frameworks. Some EU Member States have also developed national BMS, with Germany and Finland leading efforts. The BMS are essential for achieving a sustainable bioeconomy and require continuous updates and revisions to adapt to changing priorities and knowledge advances.

Learning Objectives

After studying this section, you will…

- …be able to explain why it is challenging to monitor the bioeconomy (see ► Sect. 43.1).
- …be able to describe the features and components of a bioeconomy monitoring system (see ► Sect. 43.2).
- …be able to describe the design and general structure of the EU Bioeconomy Monitoring System (see ► Sect. 43.3).

43.1 Introduction

Bioeconomy monitoring is required to track the progress of bioeconomy towards its strategic objectives or, more broadly, towards a vision or a desired improved condition. Thanks to monitoring, decision makers can assess the performance of implemented measures in terms of the original objectives and can use this information to timely introduce corrective measures when needed.

Monitoring is also essential to systematically and timely assess the impacts on the environment, the economy and the society of the bioeconomy in transition. It is worth noting that, due to the complexity of socio-economic and environmental systems, foreseeing all direct and indirect impacts of the bioeconomy is challenging.

Furthermore, synergies and trade-offs may exist across geographical scales, across pillars of sustainability, across economic sectors, making effective monitoring even more complex and relevant.

In essence, monitoring bioeconomy implies a wide range of theoretical and practical aspects to be addressed and to be effectively organised and structured in a bioeconomy monitoring system.

In the next sections, we will (i) define the features and components of a bioeconomy monitoring system, (ii) illustrate the steps required to build and implement such a system, (iii) outline the EU Bioeconomy Monitoring System and the main systems currently operated in Europe.

43.2 Main Features and Components of a Bioeconomy Monitoring System

A Bioeconomy Monitoring System (BMS) essentially responds to the need for comprehensive, reliable and comparable information on the bioeconomy and its progress to sup-

port decision-making across sectors and across the territory at different scales (European Commission 2017; Wesseler and von Braun 2017; Bracco et al. 2019).

An effective and comprehensive BMS should address all dimensions of sustainability (environmental, economic, social), be capable of highlighting and facilitating the management of potential synergies and trade-offs (Giuntoli et al. 2020; Bogdanski et al. 2021) but also of evaluating the transboundary effects of sustainable consumption and production of food, feed, bio-based products and bioenergy in a transparent way (OECD and EC-JRC 2021).

The monitoring system should furthermore provide basic information to enable further analyses and interpretation by third parties, thus contributing to the involvement, dialogue and debate between public authorities, stakeholders and citizens (Giuntoli et al. 2020).

A few essential components are required for a working BMS:

- Infrastructure to systematically collect and store quantitative evidence; many reporting systems and thematic databases exist at national or international levels covering specific sectors or thematic areas. Most data feeding a BMS do not need to be directly sourced but can be extracted from existing statistical frameworks or databases.
- Methods and tools to process the data collected, apply appropriate metrics and convert or combine the data to derive meaningful statistical indicators describing in a standardised form the aspects of interest. This is because data collected from existing frameworks may need to be normalised or transformed to fit the purpose of the BMS.
- Methods and tools to analyse and compare the indicators, transforming data into knowledge. Since the assessment of trends is key, a time series of observations is needed, and indicators are to be harmonised and compared across years. Comparison across indicators is likewise important. For example, an indicator of forest growth, telling us how much woody biomass is produced annually in a region, can be combined with a forest harvesting indicator, telling us how much primary wood is extracted annually from the same region. The ratio of the two indicators will tell us something on harvest intensity, which is ultimately related to the sustainability of woody biomass sourcing.
- Regular reporting on bioeconomy status and trends to decision makers and stakeholders. This can be seen as the essential evaluation component of the monitoring system; results should be periodically synthesised in a report written in a language accessible to a non-technical audience.
- Dissemination of the results. In addition to the regular reporting to decision makers and stakeholders, the monitoring system outcomes should be made accessible to a larger audience for transparency. The more immediate and widely used approach to this end is through web-based interactive dashboards.

To concretely design and implement a BMS, a few aspects must be addressed, which will be illustrated in the next section.

43.3 Design and Implementation of a Bioeconomy Monitoring System

General guidance to design and implement a system to monitor the sustainability of the bioeconomy at the country or macro-region level and across the globe is provided in a joint FAO and JRC report by Bogdanski et al. (2021).

The report describes a step-by-step guide on how to set up a monitoring system for the bioeconomy and outlines why it is important to develop a robust monitoring system before moving towards implementation.

The steps that should be followed to establish an effective and robust system are grouped into three stages.

1. Conceptual stage, where all the elements of the monitoring system are determined, starting from its scope and boundaries.

Indeed, given the multi-faceted nature of the bioeconomy, a clear conceptual framework is seen by many authors as very much needed (Wesseler and von Braun 2017; Robert et al. 2020). At this stage, reference definitions should be provided, and an inclusive and transparent participatory process established engaging key stakeholders among policymakers, private sector, consumers and academia.

2. Implementation stage, entailing the selection of indicators to support the assessment required by the conceptual framework; furthermore, the indicators should fit a set of agreed technical criteria (e.g. geographical coverage, timeliness, frequency of update, data accessibility, etc.). The implementation stage also involves the definition of methodologies for data collection and processing, as well as the methods for the compilation of indicators from the data collected. The selection of reference values and/or the "directionality" for each indicator are also important, the latter referring to the positive or negative sign of the impact attributed to an increase in the indicator value. For example, the indicator "GHG emissions from agriculture" has negative directionality, while "number of jobs in bioeconomy" positive.
3. Assessment and communication stage, where the trends and progress towards goals are evaluated and results communicated to enable an informed and transparent decision-making process

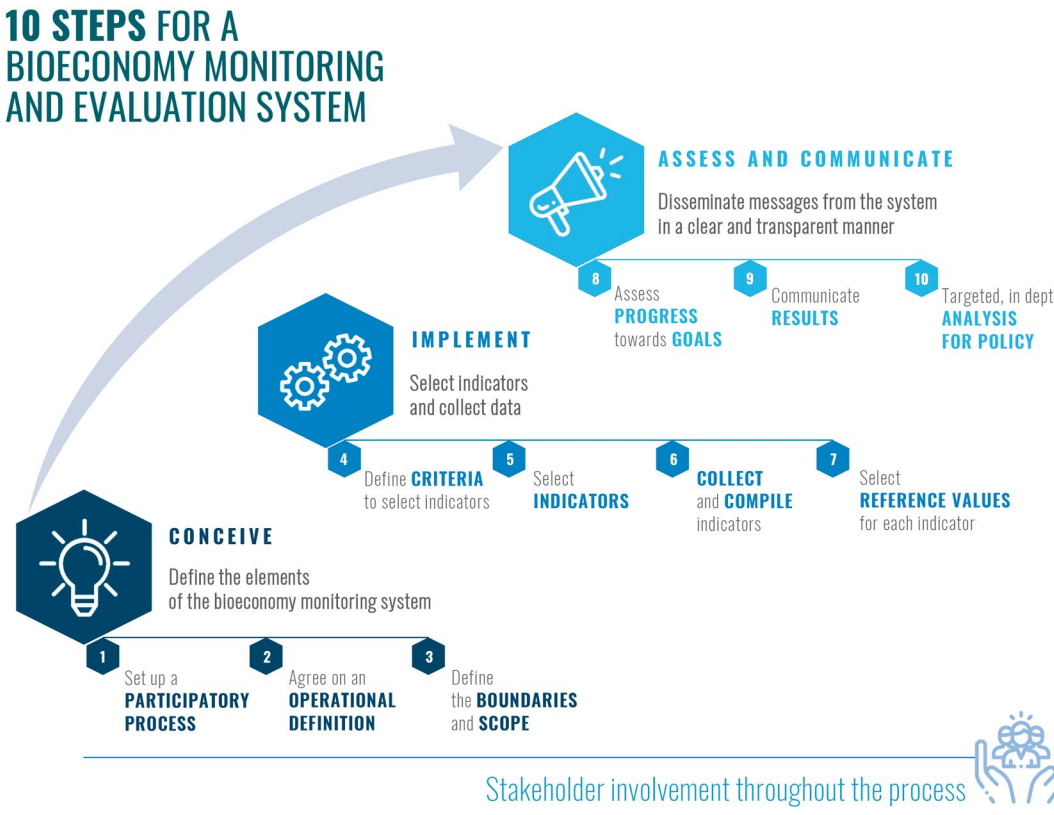


Fig. 43.1 General steps toward and effective and robust monitoring system for a sustainable bioeconomy. (Based on Bogdanski et al. 2021)

The individual steps as given in Bogdanski et al. (2021) are summarised in Fig. 43.1.

43.4 The EU Bioeconomy Monitoring System

The EU Bioeconomy Strategy of 2018 (European Commission 2018) pledges for the European Commission the development of EU-wide internationally coherent monitoring system to track economic, environmental and social progress towards a sustainable bioeconomy. This has been the legal basis for the development of the EU Bioeconomy Monitoring System (EU-BMS), stemming from the need for a transparent and comprehensive assessment of the status and progress of the bioeconomy to support decision-making (Robert et al. 2020).

The development of the EU-BMS was supported by a consultative process led by the Joint Research Centre (JRC), working in close collaboration with EU Member States, other European Commission services and key stakeholders. This participatory process resulted in a comprehensive framework, covering all aspects of sustainability (economic, social and environmental) to inform on the condition, performance and trajectory of the bioeconomy as a whole—including ecosystems and their services, primary production sectors (forestry, agriculture, aquaculture and fisheries) and bio-based industries on both systemic and sectoral levels.

The first release of the EU-BMS was launched in 2020. Its *conceptual framework*, initially designed by Giuntoli et al. (2020), operationalises the five strategic objectives of the EU Bioeconomy Strategy of 2018 into a vision for a sustainable bioeconomy. In concrete terms the framework establishes a mechanism to measure the progress of the EU bioeconomy starting from the Strategy objectives: (i) ensure food and nutrition security, (ii) manage natural resources sustainably, (iii) reduce dependence on non-renewable, unsustainable resources, (iv) mitigate and adapt to climate change and (v) strengthen European competitiveness and create job.

Following a nested approach, these broad objectives are broken down into normative criteria, which are further broken down into key components (see Fig. 43.2), each component is finally assessed with a set of quantitative indicators.

Thanks to this nested structure, the aggregation of the indicators can be done at different levels of the hierarchy, enabling targeted assessments on specific aspects or focusing on the progress towards specific objectives of the EU Bioeconomy Strategy (Mubareka et al. 2023).

As discussed in detail in Giuntoli et al. (2023), the framework of this first release of the EU-BMS reflects the political priorities expressed in the EU Bioeconomy Strategy of 2018. This framework will have to be revised, e.g. incorporating new indicators or considering new objectives, following the adoption of the new EU Bioeconomy in November 2025 (European Commission 2025), since priorities, concerns and visions are context-dependent and have changed accordingly.

Concerning the *implementation stage*, indicators were selected in order to cover all aspects foreseen by the framework and to rely on data published and periodically updated by authoritative statistical sources and existing internationally recognised monitoring and reporting frameworks, including those used for monitoring the Sustainable Development Goals, not to imply additional reporting burdens. This also ensures consistency with other international monitoring processes, enabling comparability between Member States and between EU and Member States level assessments.

The EU-BMS is operated by the JRC; at the time of writing this book not all the indicators foreseen by the framework are operationally implemented, as knowledge and data gaps still exist. Because of this, the set of indicators implemented by the EU-BMS is regularly updated and enriched as new methodologies for their estimates are developed and documented (Melim-McLeod et al. 2022; Sanchez-Jerez et al. 2023; Wydra and Kroll 2024). Knowledge gaps identified in this process may result in suggestions to improve

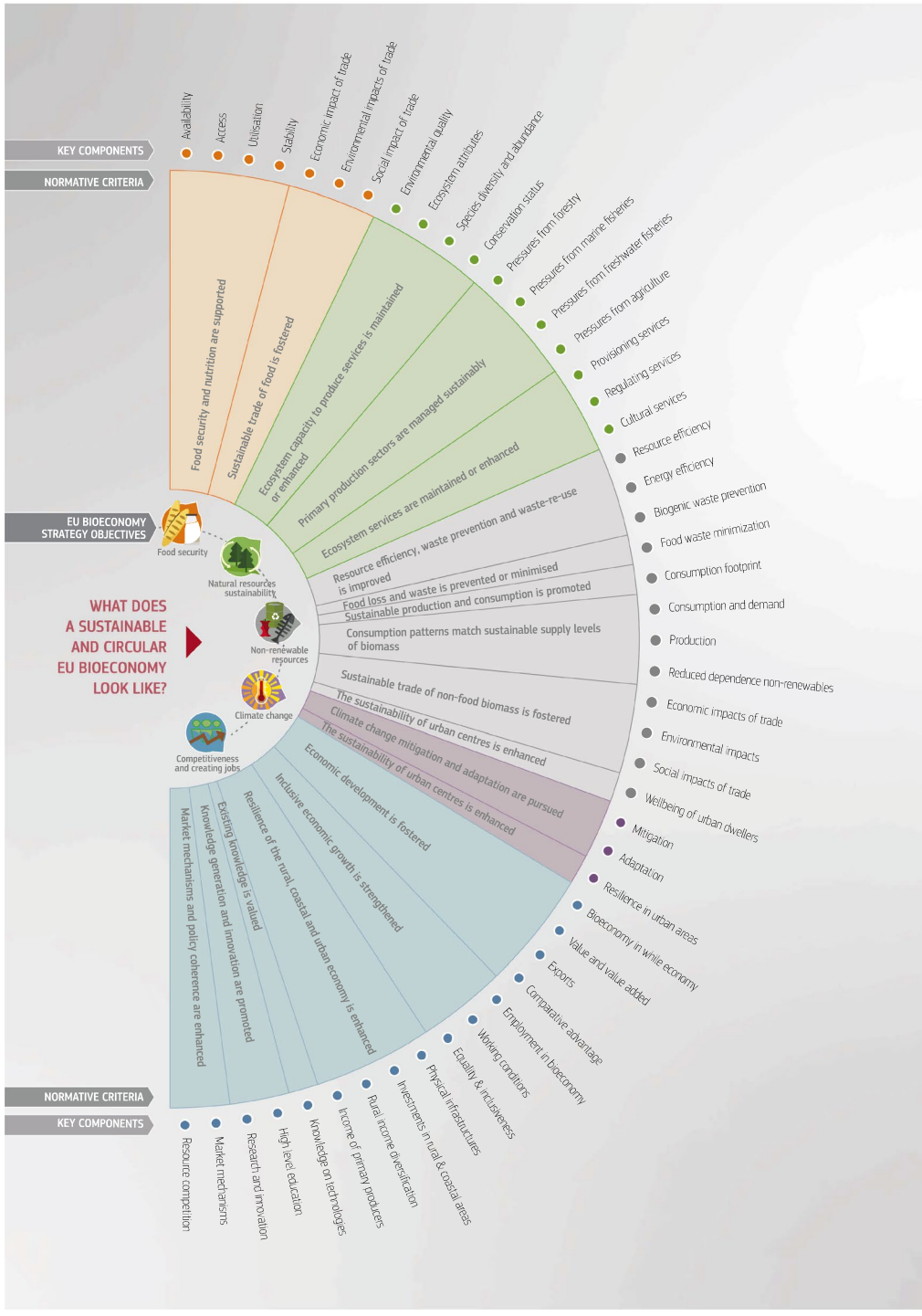


Fig. 43.2 Nested structure of the first release of EU-BMS after the EU Bioeconomy Strategy of 2018. (From Mubareka et al. (2023), licensed under CC-BY 4.0)

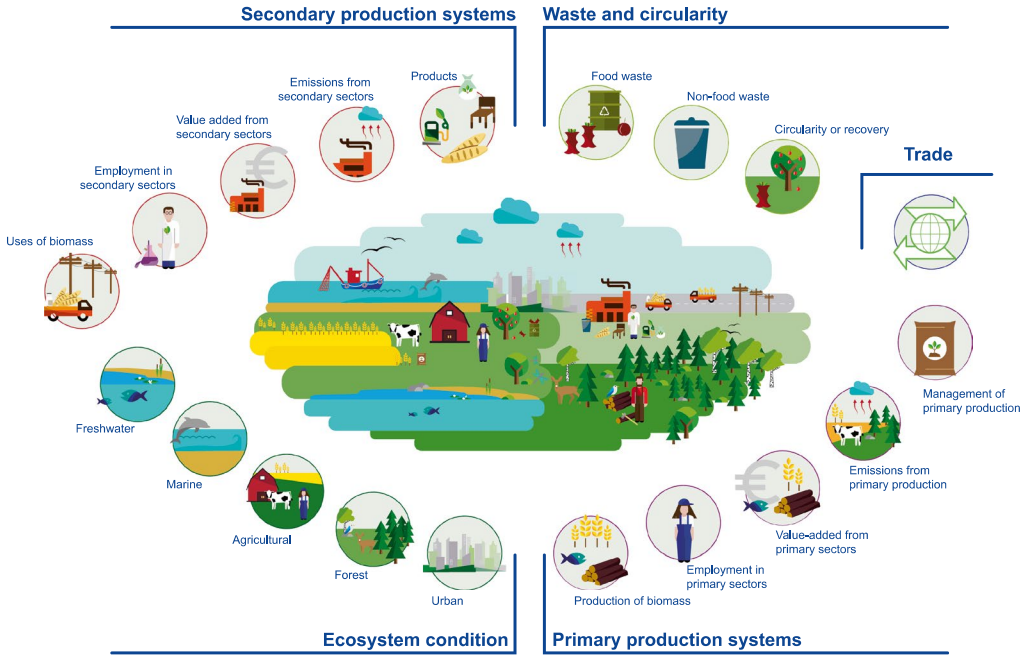


Fig. 43.3 Main dashboard of the EU-BMS operated by the European Commission's Knowledge Centre for Bioeconomy

existing data collection exercises, including proposals for new indicators to relevant statistical sources.

Concerning the *assessment and communication* stage, the EU-BMS is made publicly available via the European Commission's ► Knowledge Centre for Bioeconomy web platform, where all the implemented indicators can be accessed from the ► EU-BMS dashboards (see Fig. 43.3).

A synthesis of bioeconomy trends in the EU derived from the in-depth analysis of the full set of indicators in the EU-BMS is periodically published in a dedicated report (Mubareka et al. 2023; Korosuo et al. 2024).

43.5 Bioeconomy Monitoring in EU Member States

Since 2012, 11 EU Member States have adopted a national bioeconomy strategy and six of them have developed or are developing a BMS as part of their strategy: Germany, Finland, Ireland, Italy, the Netherlands and Portugal.

The earliest and more elaborated efforts towards the development of a monitoring system at national level are probably from Germany, supported by research projects such as ► SYMOBIO (Systemic Monitoring and Modelling of the Bioeconomy) developing the scientific basics for a systemic monitoring and modelling of the German bioeconomy with respect to sustainability aspects and ► MOBI and ► MOBI II (Monitoring Bioeconomy) developing the basics for a national monitoring system of present and future flows of biomass. An overview of efforts in Germany is available ► here.

In Finland, the project ► MontBioeco (synthesis on bioeconomy monitoring systems in the EU Member States) made an assessment identifying and comparing the different approaches to monitor the progress of bioeconomy in EU countries.

The final report of the project (Lier et al. 2018) presents an overview of existing bioeconomy strategies, policies or related initiatives and indicators to monitor and assess the importance of existing bioeconomy sectors at national level. Furthermore, it proposes a set of key indi-

cators for assessing and monitoring the progress of a bioeconomy at the national level.

A recent overview of national bioeconomy strategies and related initiatives, as well as of bioeconomy monitoring frameworks at the national level, is also available in Korosuo et al. (2024).

Questions

1. What are the key components of a Bioeconomy Monitoring System (BMS), and how do they contribute to the system's effectiveness?
2. Why is it important for a BMS to address all dimensions of sustainability, and what role do synergies and trade-offs play in its function?
3. Which steps need to be followed to establish an effective and robust bioeconomy monitoring system?
4. What are the five strategic objectives of the EU Bioeconomy Strategy of 2018 and how are they addressed in the EU-BMS?

Answers

1. The key components of a Bioeconomy Monitoring System (BMS) include infrastructure for data collection, methods and tools for data processing, analysis tools for comparing indicators, regular reporting and the dissemination of results. The infrastructure enables systematic collection and storage of quantitative data from existing databases. The data processing tools help to standardise and derive meaningful indicators. Analysis tools allow for the comparison of trends and indicators over time, aiding in the assessment of bioeconomy sustainability. Regular reports provide stakeholders with synthesised information, while dissemination via interactive dashboards ensures transparency and broad access to the results.
2. It is important for a BMS to address environmental, economic and social dimensions of sustainability to provide a comprehensive view of the bioeconomy. By identifying synergies (where actions benefit multiple sustainability aspects) and trade-offs (where one dimension may negatively impact another), the system can guide decision-making and highlight areas where improvements can be made. This holistic approach ensures that the bioeconomy progresses in a balanced and sustainable manner across all sectors
3. At the conceptual stage, the key elements of the monitoring system need to be determined. This involves setting up an inclusive and transparent participatory process, providing all necessary reference definitions as well as defining the scope and boundaries of the bioeconomy monitoring system. At the following implementation stage, assessment criteria need to be defined, and fitting indicators need to be selected. In addition, the methods for the compilation of indicators as well as reference values and/or the "directionality" for each indicator need to be defined. Lastly, during the assessment and communication stage, the trends and progress towards goals are evaluated, and results are communicated to enable an informed and transparent decision-making process.
4. The five strategic objectives of the EU Bioeconomy Strategy of 2018 are: (i) ensuring food and nutrition security, (ii) managing natural resources sustainably, (iii) reducing dependence on non-renewable, unsustainable resources, (iv) mitigating and adapt to climate change and (v) strengthening European competitiveness and create job opportunities. Within the EU-BMS, all objectives are broken down into normative criteria, which are further broken down into key components that can be assessed by a set of quantitative indicators.

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