

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



UNIVERSITY OF
HOHENHEIM

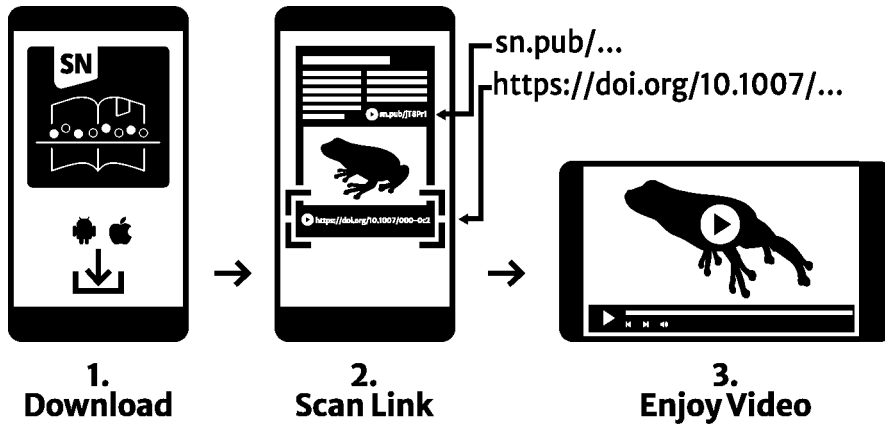


OPEN ACCESS

 Springer

Bioeconomy

Springer Nature More Media App



Support: customerservice@springernature.com

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




Springer



UNIVERSITY OF
HOHENHEIM

Editors

Iris Lewandowski 
Institute of Crop
Science, Department of Biobased
Resources in the Bioeconomy
University of Hohenheim
Stuttgart, Germany

Philipp Scheurich
Department of Biobased Resources
in the Bioeconomy (340b)
University of Hohenheim
Stuttgart, Germany

Valentin Schlecht
Institute of Crop
Science, Department of Biobased
Resources in the Bioeconomy
University of Hohenheim
Stuttgart, Germany

Lina Mayorga-Duarte
Department of Biobased Resources
in the Bioeconomy (340b)
University of Hohenheim
Stuttgart, Germany

Ricardo Vargas-Carpintero
Department of Biobased Resources
in the Bioeconomy (340b)
University of Hohenheim
Stuttgart, Germany

Jan Weik
Institute of Crop
Science, Department of Biobased
Resources in the Bioeconomy
University of Hohenheim
Stuttgart, Germany

Editorial Contact: Annette Klaus



ISBN 978-3-032-09097-3 ISBN 978-3-032-09098-0 (eBook)
<https://doi.org/10.1007/978-3-032-09098-0>

This work was supported by Iris Lewandowski.

© The Editor(s) (if applicable) and The Author(s) 2018, 2026. This book is an open access publication.

Open Access This book is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this book are included in the book's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the book's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

If disposing of this product, please recycle the paper.

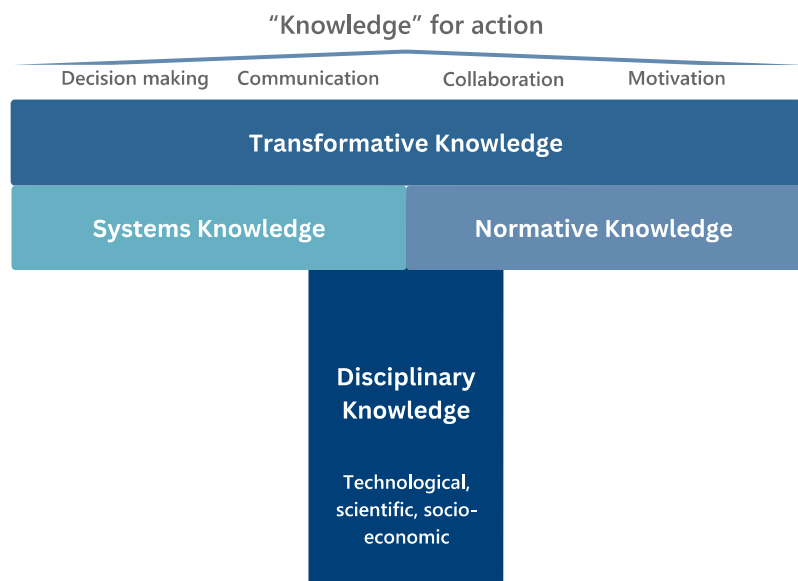
This textbook is dedicated to Prof. Dr. Stephan Dabbert, President of the University of Hohenheim, who sadly passed away on October 1, 2024, while this book underwent editorial revision. Prof. Dr. Dabbert was always a strong advocate of the bioeconomy in research and teaching at the University of Hohenheim. 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,



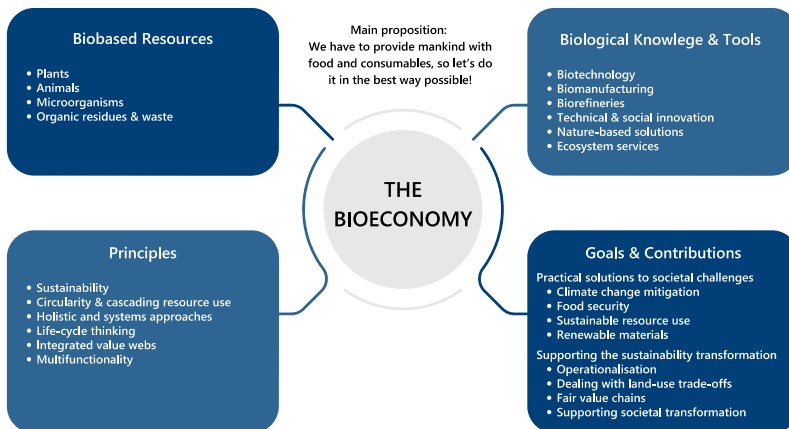
■ Fig. 1 T-shaped qualification profile

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.

Iris Lewandowski

Stuttgart, Germany

Lina Mayorga-Duarte

Stuttgart, Germany

Philipp Scheurich

Stuttgart, Germany

Ricardo Vargas-Carpintero

Stuttgart, Germany

Valentin Schlecht

Stuttgart, Germany

Jan Weik

Stuttgart, Germany

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

Contents

I Bioeconomy Context, Concepts, and Principles

1	Context	3
	<i>Iris Lewandowski, Lina Mayorga-Duarte, Philipp Scheurich, Valentin Schlecht, Ricardo Vargas-Carpintero, and Jan Weik</i>	
2	Bioeconomy Concepts	19
	<i>Regina Birner, Valentin Schlecht, Jan Weik, Ricardo Vargas-Carpintero, and Iris Lewandowski</i>	
3	Guiding Principles of a Bioeconomy	47
	<i>Valentin Schlecht, Marielle Trenkner, Andrea Knierim, and Ricardo Vargas-Carpintero</i>	
4	Bio-Based Value Chains and Webs	73
	<i>Ricardo Vargas-Carpintero and Valentin Schlecht</i>	

II Biomass Production Systems

5	Bio-Based Resources	99
	<i>Christian Zörb and Iris Lewandowski</i>	
6	Agricultural Production	121
	<i>Iris Lewandowski, Melvin Lippe, Moritz von Cossel, Evelyn Reinmuth, and Joaquín Castro-Montoya</i>	
7	Urban Agriculture	161
	<i>Bastian Winkler</i>	
8	Forestry	173
	<i>Gerhard Langenberger and Melvin Lippe</i>	
9	Blue Bioeconomy	215
	<i>Johannes Pucher</i>	
10	Microalgae	231
	<i>Sebastian Weickert and Konstantin Frick</i>	
11	Insects	247
	<i>Iris Lewandowski</i>	
12	Residual Biomass: Origins, Characteristics, Composition	253
	<i>Evelyn Reinmuth and Philipp Scheurich</i>	

13	Biogenous Waste Management	277
	<i>Stefan Salhofer and Erwin Binner</i>	
14	Bio-Based Fertilizing Products: Closing Nutrient Loops by Recycling	287
	<i>Marielle Trenkner, Benedikt Müller, and Andrea Bauerle</i>	
15	Digitalization in Agricultural Production	297
	<i>Anthony Stein</i>	
16	Economics of Primary Production	317
	<i>Christian Lippert</i>	
III Processing		
17	Biomass Use and Biorefineries	335
	<i>Iris Lewandowski and Ricardo Vargas-Carpintero</i>	
18	Biotechnological Conversion	349
	<i>Karin Moß, Marius Henkel, and Rudolf Hausmann</i>	
19	Thermochemical Conversion	365
	<i>Andrea Kruse</i>	
20	Food Processing	385
	<i>Myriam Loeffler and Jörg Hinrichs</i>	
21	Dairy and Meat Analogues	403
	<i>Lisa M. Berger, Monika Gibis, and Jochen Weiss</i>	
22	Transforming Bio-Based Sidestreams and Raw Materials into Food Ingredients	431
	<i>Mario Jekle, Jannika Dombrowski, Sandra Renz, and Margit Jekle</i>	
23	Extraction of Fibres for Non-food Applications	451
	<i>Manuel Clauss and Hermann Dauser</i>	
24	Bioenergy: Energy Derived from Biomass	459
	<i>Iris Lewandowski</i>	
25	Digitalization in Processing	469
	<i>Elia Henrichs, Julia Senge, and Christian Krupitzer</i>	
26	Process and Product Cost Assessment	479
	<i>Nicolaus Dahmen, Jörg Sauer, and Simon Wodarz</i>	

IV Markets for Bio-based Products & Economics for a Sustainable Bioeconomy

- 27 **Markets of Bio-based Resources and Products** 497
Kirsten Boysen-Urban, Ole Boysen, and Carolina Schiesari
- 28 **Economics for a Sustainable Bioeconomy—Theory and Policies**..... 531
Franziska Schuenemann, Marius Boesino, Pranav Patil, and Alina J. Rossa

V Stakeholders of the Bioeconomy

- 29 **Governance of the Bioeconomy** 559
Regina Birner
- 30 **The Role of Farmers and Farmer Associations** 575
Nicola Bühler, Rebecca Hansen, Tessa Jensen-Auvermann, Pamela Laven, and Sebastian Hess
- 31 **Sustainability Management at Farm Level** 589
Iris Lewandowski and Moritz Wagner
- 32 **Fostering Innovation Systems for the Transition to a Bioeconomy** 599
Andreas Pyka and Klaus Prettnner
- 33 **Inclusive Innovation in the Bioeconomy** 613
Lotte Asveld
- 34 **Entrepreneurial Ventures and the Bioeconomy** 625
Andreas Kuckertz, Elisabeth S. C. Berger, C. Arturo Morales Reyes, and Sebastian Hinderer
- 35 **Sustainability Management at Corporate Level** 637
Iris Lewandowski and Moritz Wagner
- 36 **Consumers in the Bioeconomy** 645
Ramona Weinrich, Stefan Hirsch, and Laura Henn
- 37 **Inter- and Transdisciplinary Research in Bioeconomy** 665
Andrea Knierim, Sangeun Bae, Beatriz Herrera, and Patcharin Sae-heng
- 38 **The Bioeconomist** 693
Lina Mayorga-Duarte, Jan Lask, Ricardo Vargas-Carpintero, and Jan Weik

VI Guiding the Bioeconomy Transition

39	Conditions for a Responsible Bioeconomy	711
	<i>Markus Vogt</i>	
40	Exploring the Biodiversity–Bioeconomy Nexus	717
	<i>Arndt Feuerbacher, Ricardo Vargas-Carpintero, Jan Weik, and Valentin Schlecht</i>	
41	Sustainability Assessment	735
	<i>Jan Weik, Valentin Schlecht, Nirvana A. Marting Vidaurre, Jan Lask, and Moritz Wagner</i>	
42	Modelling to Support the Bioeconomy Transition	763
	<i>Christian Sponagel, Jan Weik, Christian Troost, and Elisabeth Angenendt</i>	
43	Bioeconomy Monitoring	795
	<i>Andrea Camia</i>	

Contributors

Elisabeth Angenendt Institute of Farm Management, Department of Farm Management, University of Hohenheim, Stuttgart, Germany

Lotte Asveld Department of Biotechnology, Section of Biotechnology and Society, Delft University of Technology, Delft, The Netherlands

Sangeun Bae Institute of Social Sciences in Agriculture, Department of Communication and Advisory Services in Rural Areas, University of Hohenheim, Stuttgart, Germany

Andrea Bauerle Institute of Crop Science, Department of Biobased Resources in the Bioeconomy, University of Hohenheim, Stuttgart, Germany

Elisabeth S. C. Berger Institute for Entrepreneurship, JKU Business School, Johannes Kepler University, Linz, Austria

Lisa M. Berger Department of Food Material Science, University of Hohenheim, Stuttgart, Germany

Erwin Binner Institute of Waste Management and Circularity, BOKU-University of Natural Resources and Live Sciences Vienna, Vienna, Austria

Regina Birner Hans-Ruthenberg-Institute, Department of Social and Institutional Change in Agricultural Development, University of Hohenheim, Stuttgart, Germany

Marius Boesino Institute of Economics, Department of Bioeconomy & Computational Science Hub, University of Hohenheim, Stuttgart, Germany

Ole Boysen School of Agriculture and Food Science, University College Dublin, Dublin, Ireland

Kirsten Boysen-Urban Hans-Ruthenberg-Institute for Tropical Agricultural Sciences, Department of International Agricultural Trade and Food Security, University of Hohenheim, Stuttgart, Germany

Nicola Bühler Institute of Agricultural Policy and Markets, Research Centre of Cooperatives, University of Hohenheim, Stuttgart, Germany

Andrea Camia European Commission, Joint Research Centre (JRC), Ispra, Italy

Joaquín Castro-Montoya Institute for Agrifood and Environmental Sciences, Faculty of Agricultural Sciences, University of El Salvador, San Salvador, El Salvador

Manuel Clauss Fibers365 GmbH, Lenningen, Germany

Moritz von Cossel Institute of Crop Sciences, Department of Biobased Resources in the Bioeconomy, University of Hohenheim, Stuttgart, Germany

Nicolaus Dahmen Institute of Catalysis Research and Technology, Karlsruhe Institute of Technology, Karlsruhe, Germany

Hermann Dauser Fibers365 GmbH, Lenningen, Germany

Jannika Dombrowski Nestlé Product Technology Centre Nutrition, Department of Science and Technology, Société des Produits Nestlé SA, Konolfingen, Switzerland

Arndt Feuerbacher Institute of Agricultural Policy and Markets, Department of Economic-Ecological Policy Modeling, University of Hohenheim, Stuttgart, Germany

KomBioTa - Center of Biodiversity and Integrative Taxonomy, University of Hohenheim, Stuttgart, Germany

Konstantin Frick Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB, Stuttgart, Germany

Monika Gibis Department of Food Material Science, University of Hohenheim, Stuttgart, Germany

Rebecca Hansen Institute of Agricultural Policy and Markets, Research Centre of Cooperatives, University of Hohenheim, Stuttgart, Germany

Rudolf Hausmann Institute of Food Science and Biotechnology, Department of Bioprocess Engineering, University of Hohenheim, Stuttgart, Germany

Marius Henkel TUM School of Life Sciences, Cellular Agriculture, Technical University of Munich (TUM), Munich, Germany

Laura Henn Institute of Education, Work and Society, Department of Sustainable Behavior and Management, University of Hohenheim, Stuttgart, Germany

Elia Henrichs Department of Food Informatics & Computational Science Hub, University of Hohenheim, Stuttgart, Germany

Beatriz Herrera Institute of Social Sciences in Agriculture, Department of Communication and Advisory Services in Rural Areas, University of Hohenheim, Stuttgart, Germany

Sebastian Hess Institute of Agricultural Policy and Markets, Research Centre of Cooperatives, University of Hohenheim, Stuttgart, Germany

Sebastian Hinderer Institute of Marketing & Management, Entrepreneurship Research Group (570C), University of Hohenheim, Stuttgart, Germany

Jörg Hinrichs Institute of Food Science and Biotechnology, Department of Soft Matter Science and Dairy Technology, University of Hohenheim, Stuttgart, Germany

Stefan Hirsch Institute of Farm Management, Department of Management in Agribusiness, University of Hohenheim, Stuttgart, Germany

Margit Jekle Department of Food Technology, SRH Fernhochschule, Riedlingen, Germany

Mario Jekle Institute of Food Science and Biotechnology, Department of Plant-based Foods, University of Hohenheim, Stuttgart, Germany

Tessa Jensen-Auermann Institute of Agricultural Policy and Markets, Research Centre of Cooperatives, University of Hohenheim, Stuttgart, Germany

Andrea Knierim Institute of Social Sciences in Agriculture, Department of Communication and Advisory Services in Rural Areas (430a), University of Hohenheim, Stuttgart, Germany

Christian Krupitzer Department of Food Informatics & Computational Science Hub, University of Hohenheim, Stuttgart, Germany

Andrea Kruse Institute of Agricultural Engineering, Department of Conversion Technologies of Biobased Resources, University of Hohenheim, Stuttgart, Germany

Andreas Kuckertz Institute of Marketing & Management, Entrepreneurship Research Group (570C), University of Hohenheim, Stuttgart, Germany

Gerhard Langenberger Sustainable Agricultural Supply Chains Initiative (SASI), Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Bonn, Germany

Jan Lask Institute of Crop Science, Department of Biobased Resources in the Bioeconomy, University of Hohenheim, Stuttgart, Germany

Pamela Laven Institute of Agricultural Policy and Markets, Research Centre of Cooperatives, University of Hohenheim, Stuttgart, Germany

Iris Lewandowski Institute of Crop Science, Department of Biobased Resources in the Bioeconomy, University of Hohenheim, Stuttgart, Germany

Melvin Lippe Johann Heinrich von Thünen Institute, Institute of Forestry, Hamburg, Germany

Christian Lippert Department of Production Theory and Resource Economics, University of Hohenheim, Stuttgart, Germany

Myriam Loeffler Meat Technology and Science of Protein-Rich Foods (MTSP), Department of Microbial and Molecular Systems, KU Leuven, Ghent, Belgium

Nirvana A. Marting Vidaurre SUSTAIN Unit, LCSA Group, Luxembourg Institute of Science and Technology, Esch-sur-Alzette, Luxembourg

Lina Mayorga-Duarte Institute of Crop Science, Department of Biobased Resources in the Bioeconomy, University of Hohenheim, Stuttgart, Germany

Karin Moß Institute of Food Science and Biotechnology, Department of Bioprocess Engineering, University of Hohenheim, Stuttgart, Germany

Benedikt Müller Institute of Crop Science, Department of Biobased Resources in the Bioeconomy, University of Hohenheim, Stuttgart, Germany

Pranav Patil Institute of Economics, Department of Bioeconomy & Computational Science Hub, University of Hohenheim, Stuttgart, Germany

Klaus Prettner Department of Economics, WU Vienna, Vienna, Austria

Johannes Pucher German Federal Institute for Risk Assessment, Department German Centre for the Protection of Laboratory Animals and Experimental Toxicology, Berlin, Germany

Andreas Pyka Institute of Economics, Innovation economics, University of Hohenheim, Stuttgart, Germany

Evelyn Reinmuth Institute of Crop Sciences, Department of Biobased Resources in the Bioeconomy, University of Hohenheim, Stuttgart, Germany

Sandra Renz Core Facility Hohenheim, Analytical Chemistry Unit and Technology Transfer, University of Hohenheim, Stuttgart, Germany

C. Arturo Morales Reyes Institute of Marketing & Management, Entrepreneurship Research Group (570C), University of Hohenheim, Stuttgart, Germany

Alina J. Rossa Institute of Economics, Department of Bioeconomy & Computational Science Hub, University of Hohenheim, Stuttgart, Germany

Patcharin Sae-heng Institute of Social Sciences in Agriculture, Department of Communication and Advisory Services in Rural Areas, University of Hohenheim, Stuttgart, Germany

Stefan Salhofer Institute of Waste Management and Circularity, BOKU-University of Natural Resources and Live Sciences Vienna, Vienna, Austria

Jörg Sauer Institute of Catalysis Research and Technology, Karlsruhe Institute of Technology, Karlsruhe, Germany

Philipp Scheurich Institute of Crop Science, Department of Biobased Resources in the Bioeconomy, University of Hohenheim, Stuttgart, Germany

Carolina Schiesari Luiz de Queiroz College of Agriculture (ESALQ/USP), Department of Economics, Administration and Sociology, University of São Paulo, São Paulo, Brazil

Valentin Schlecht Institute of Crop Science, Department of Biobased Resources in the Bioeconomy, University of Hohenheim, Stuttgart, Germany

Franziska Schuenemann Institute of Economics, Department of Bioeconomy & Computational Science Hub, University of Hohenheim, Stuttgart, Germany

Julia Senge Department of Food Informatics & Computational Science Hub, University of Hohenheim, Stuttgart, Germany

Christian Sponagel Institute of Farm Management, Department of Farm Management, University of Hohenheim, Stuttgart, Germany

Anthony Stein Institute of Agricultural Engineering, Department of Artificial Intelligence in Agricultural Engineering, University of Hohenheim, Stuttgart, Germany

Marielle Trenkner Institute of Crop Science, Department of Biobased Resources in the Bioeconomy, University of Hohenheim, Stuttgart, Germany

Christian Troost Hans-Ruthenberg-Institute for Tropical Agricultural Sciences, Department of Land Use Economics, University of Hohenheim, Stuttgart, Germany

Ricardo Vargas-Carpintero Institute of Crop Science, Department of Biobased Resources in the Bioeconomy, University of Hohenheim, Stuttgart, Germany

Markus Vogt Faculty of Catholic Theology, Ludwig-Maximilians University, Munich, Germany

Moritz Wagner Institute of Applied Ecology, Geisenheim University, Geisenheim, Germany

Sebastian Weickert Institute of Crop Sciences, Department of Biobased Resources in the Bioeconomy, University of Hohenheim, Stuttgart, Germany

Jan Weik Institute of Crop Science, Department of Biobased Resources in the Bioeconomy, University of Hohenheim, Stuttgart, Germany

Ramona Weinrich Institute of Agricultural Policy and Markets, Department of Consumer Behaviour in the Bioeconomy, University of Hohenheim, Stuttgart, Germany

Jochen Weiss Department of Food Material Science, University of Hohenheim, Stuttgart, Germany

Bastian Winkler Institute of Crop Science, Department of Biobased Resources in the Bioeconomy, University of Hohenheim, Stuttgart, Germany

Simon Wodarz Institute of Catalysis Research and Technology, Karlsruhe Institute of Technology, Karlsruhe, Germany

Christian Zörb Institute of Crop Science, Department of Quality of Plant Products, University of Hohenheim, Stuttgart, Germany

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.

Contents

- Chapter 1** **Context – 3**
- Chapter 2** **Bioeconomy Concepts – 19**
- Chapter 3** **Guiding Principles of a Bioeconomy – 47**
- Chapter 4** **Bio-Based Value Chains and Webs – 73**

Context

Iris Lewandowski, Lina Mayorga-Duarte, Philipp Scheurich, Valentin Schlecht, Ricardo Vargas-Carpintero, and Jan Weik



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

Contents

- 1.1 Fossil Resources and Climate Change – 4
- 1.2 Bio-based Resources – 7
- 1.3 Planetary Boundaries and Limitation of Natural Resources: Current Status – 8
- 1.4 Population Growth and Food Security – 11
- 1.5 The Role of the Bioeconomy in the Face of Global Challenges, Wicked Problems, and the Sustainability Transformation – 13

References – 17

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/978-3-032-09098-0_1. 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.

© The Author(s) 2026

I. Lewandowski et al. (eds.), *Bioeconomy*, https://doi.org/10.1007/978-3-032-09098-0_1

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

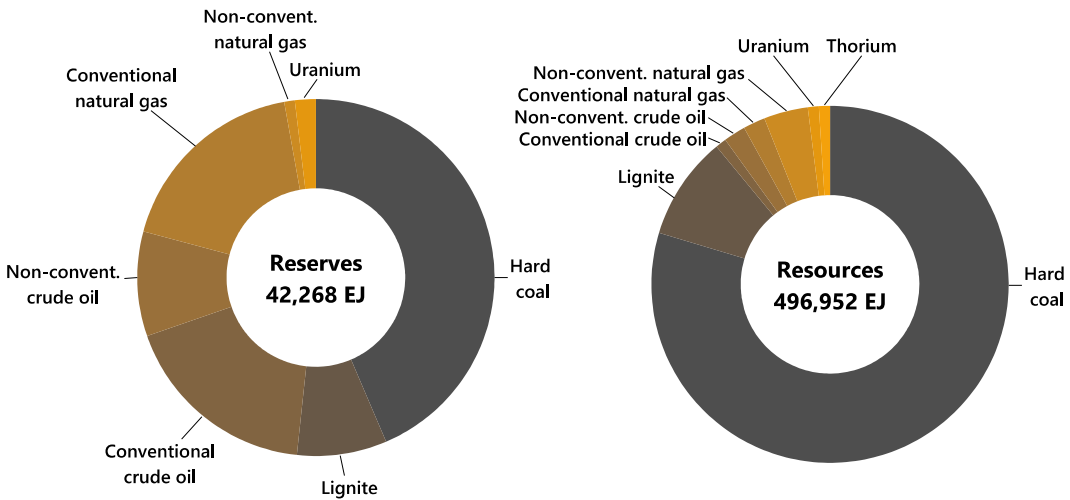
fossil oil, coal, gas and uranium and learnt how to put them into use, biomass covered all human needs for food, energy and materials.

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 (CO₂) 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 ₂ O	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

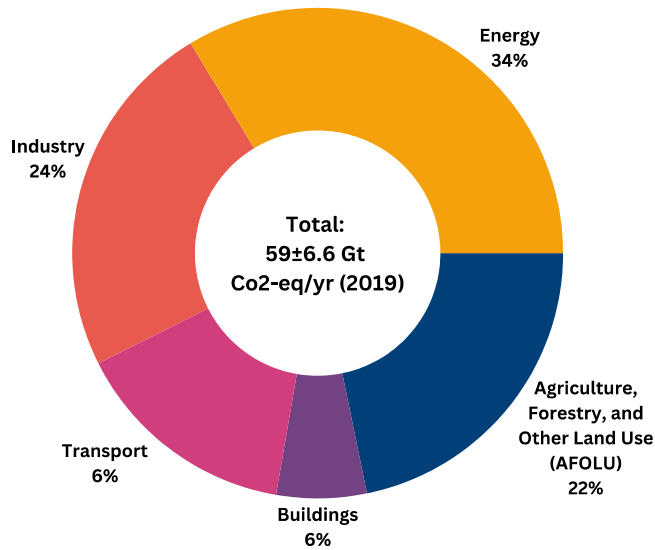
^a IPCC (2006)

^bOwn 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 (CO₂) are released into the atmosphere (see ■ Table 1.1).

The atmospheric concentrations of the major greenhouse gases (GHG) carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) 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 CO₂-equivalents) of net global GHG emissions coming from the energy sector, 24% (14 Gt CO₂-equivalents) from industry, 22% (13 Gt CO₂-equivalents) from AFOLU (agriculture, forestry, land use change), 15% (8.7 Gt CO₂-equivalents) from transport and 6% (3.3 Gt CO₂-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 CO₂-equivalents (see ■ Fig. 1.2). CO₂-equivalents include the weighted effect of CO₂ (GWP_{100 yr} = 1), CH₄



■ **Fig. 1.2** Total anthropogenic greenhouse gas (GHG) emissions (gigatons of CO₂-equivalent per year, GtCO₂-eq/yr) from economic sectors in 2019. (Based on IPCC 2023)

(GWP_{100 yr} = 28) and N₂O (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.

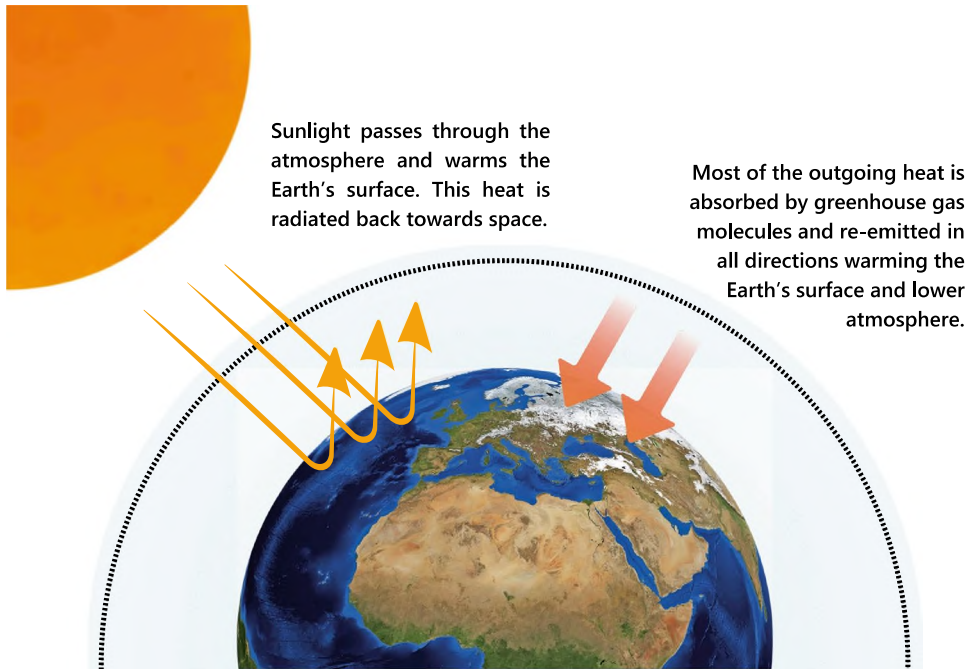
Greenhouse gases (GHGs) in the atmosphere lead to the so-called *greenhouse effect*. The Earth's surface absorbs some of the energy from sunlight and heats up. It cools down again by giving off this energy in a different form, called infrared radiation. This infrared radiation escapes back to space but, 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 CO₂)
- 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 CO₂-induced warming remains below 2 °C would require cumulative CO₂ emissions from all anthropogenic sources to remain below about 3650 GtCO₂ (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, CO₂ 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 CO₂ 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 CO₂ from the atmosphere and its release back into the atmosphere. Therefore, biomass is often considered “CO₂ neutral” and “renewable” because the same amount of CO₂ 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.

Excursus 1.1: Renewable Carbon Economy

The principle of renewable carbon is based on the circumstance that climate change is not fundamentally a “CO₂ 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 CO₂) into the atmosphere that would otherwise remain underground. If this inflow of fossil carbon were halted, atmospheric CO₂ levels would stabilize since CO₂ 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 stabilize 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 CO₂) 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 through 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 bio-economy, 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

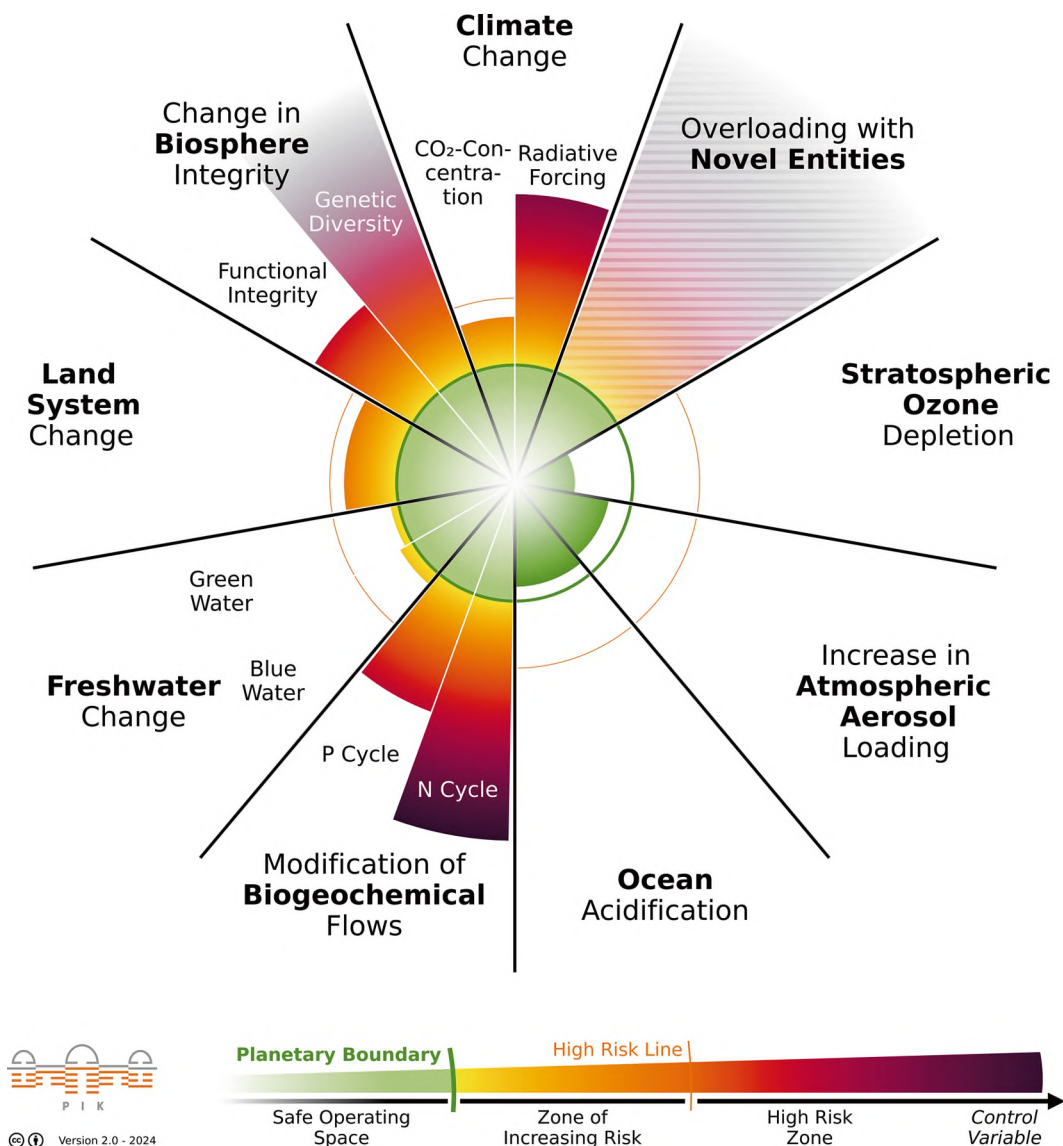


Fig. 1.4 The nine planetary boundaries, update for 2024. The green-shaded area represents the safe operating space. (From Potsdam Institute for Climate Impact Research (PIK), licensed under CC BY 4.0)

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

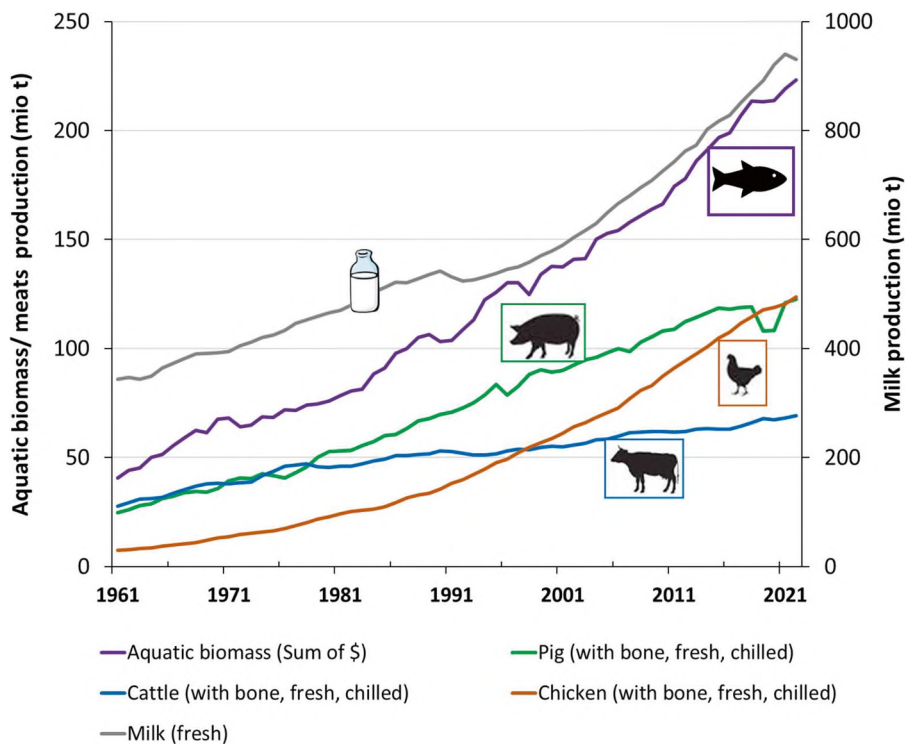


Fig. 1.5 Global production of aquatic biomass^(S) from capture fishery and aquaculture, fresh meats and milk in 1961 to 2022 based on FAO (2024a, b); ^(S) refers to: aquatic plants, seaweed and algae; aquaculture (freshwater, marine, & brackish waters); capture fishery (inland & marine waters)

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 (▶ Chaps. 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

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 CO₂ 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 biode-

gradable 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.

References

- Angermeier PL, Karr JR (1994) Biological integrity versus biological diversity as policy directives. *Bioscience*. <https://doi.org/10.2307/1312512>
- Aulakh J, Regmi A (2013) Post-harvest food losses estimation-development of consistent methodology. First Meeting of the Scientific Review Committee of the Food and Agricultural Organization of the UN. Accessed 22 Dec 2014
- BGR– Bundesanstalt für Geowissenschaften und Rohstoffe (2024) BGR Energy Study 2023. Data and Developments Concerning German and Global Energy Supplies (25). BGR, Hannover, Germany; <https://doi.org/10.25928/es-2023-en>
- Bruinsma J (2009) The Resource Outlook to 2050: by how much do land, water and crop yields need to increase by 2050? In: FAO expert meeting. <https://doi.org/10.1016/B978-0-323-10199-8.00006-2>
- European Commission (2014) Report on critical raw materials for the EU - critical raw materials profiles. In cooperation with Claudia Wulz (ENTR). European Commission, Brussels
- FAO (2011) The state of the world's land and water resources for food and agriculture (SOLAW)—managing systems at risk. Food and Agriculture Organization of the United Nations/Earthscan, Rome/London
- FAO (2021) The state of the world's land and water resources for food and agriculture—systems at breaking point. Synthesis report 2021. FAO, Rome. <https://doi.org/10.4060/cb7654en>
- FAO (2024a) FishStat: Global production by production source 1961–2022. Accessed on 10 Dec 2024. In: FishStatJ. Available at www.fao.org/fishery/en/statistics/software/fishstatj. Licence: CC-BY-4.0
- FAO (2024b) FAOStat: Global production by production source 1961–2022. Accessed on 10 Dec 2024. In FAOStat available at <https://www.fao.org/faostat/en/#data/QCL>. Licence: CC-BY-4.0
- Hilger T, Lewandowski I, Winkler B et al (2015) Seeds of change: plant genetic resources and people's livelihoods. In: *Agroecology*. INTECH open sciencelopen minds, Rijeka, pp 123–146
- IPCC (2006) In: Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (eds) Guidelines for national greenhouse gas inventories, prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan
- IPCC (2014) Climate change 2014: synthesis report. In: Core Writing Team, Pachauri RK, Meyer LA (eds) Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, 151 pp. https://www.ipcc.ch/pdf/assessmentreport/ar5/syr/AR5_SYR_FINAL_All_Topics.pdf. Accessed 31 Dec 2016
- IPCC (2023) Climate change 2024: synthesis report of the IPCC sixth assessment report. IPCC, Geneva. <https://www.ipcc.ch/report/sixth-assessment-report-cycle/>
- Karr JR, Dudley DR (1981) Ecological perspective on water quality goals. *Environ Manag* 5(1):55–68. <https://doi.org/10.1007/BF01866609>
- Kopp OC (2024) Fossil fuel. *Britannica*. <https://www.britannica.com/science/fossil-fuel>. Accessed 23 Oct 2024
- Lambin EF, Turner BL, Geist HJ et al (2001) The causes of land use and land cover change: moving beyond the myths. *Glob Environ Chang* 11(4):261–269
- National Aeronautics and Space Administration (2024) The causes of climate change. <https://science.nasa.gov/climate-change/causes/>. Last accessed 23 Oct 2024
- Pretty J, Toulmin C, Williams S (2011) Sustainable intensification in African agriculture. *Int J Agric Sustain*. <https://doi.org/10.3763/ijas.2010.0583>
- Priefer C, Jörissen J, Frör O (2017) Pathways to shape the bioeconomy. *Resources* 6(1). <https://doi.org/10.3390/resources6010010>
- REN21 (2016) Renewables 2016 Global Status Report. REN21 Secretariat, Paris. ISBN 978–3–9818107-0-7

- Richardson K, Steffen W, Lucht W et al (2023) Earth beyond six of nine planetary boundaries. *Sci Adv* 9(37). <https://doi.org/10.1126/sciadv.adh2458>
- Smeets EMW, Faaij APC, Lewandowski IM et al (2007) A bottom-up assessment and review of global bio-energy potentials to 2050. *Prog Energy Combust Sci*. <https://doi.org/10.1016/j.pecs.2006.08.001>
- Smith P, Martino D, Cai Z et al (2007) Agriculture. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) *Climate change 2007: mitigation, contribution of Working Group III to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK/New York
- Steffen W, Richardson K, Rockstrom J et al (2015) Planetary boundaries: guiding human development on a changing planet. *Science*. <https://doi.org/10.1126/science.1259855>
- Stockholm Resilience Center (2023) Planetary boundaries. <http://www.stockholmresilience.org/research/planetary-boundaries.html>. Last accessed 23 Oct 2024
- UNEP (1997) In: Middleton N, Thomas D (eds) *World atlas of desertification*. Copublished in the US, Central and South America by Wiley, London/New York
- UNEP (2023) *Frontiers 2023. What's Cooking? An assessment of the potential impacts of selected novel alternatives to conventional animal products*. UNEP, Nairobi. <https://doi.org/10.59117/20.500.11822/44236>
- von Berg C, Carus M et al (2023) Renewable carbon as a guiding principle for sustainable carbon cycles. *Renewable Carbon Initiative, Hürth*. <https://doi.org/10.52548/CXFS7519>
- Welp LR, Keeling RF, Meijer HAJ et al (2011) Interannual variability in the oxygen isotopes of atmospheric CO₂ driven by El Niño. *Nature*. <https://doi.org/10.1038/nature10421>

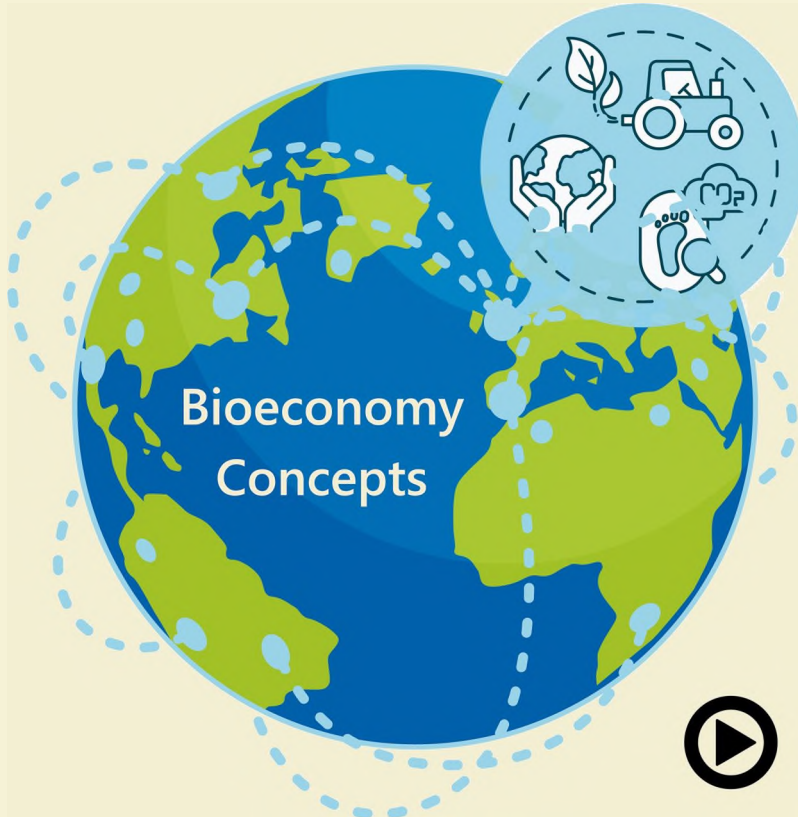
Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.



Bioeconomy Concepts

*Regina Birner, Valentin Schlecht, Jan Weik,
Ricardo Vargas-Carpintero, and Iris Lewandowski*



■ Fig. 2.0 Bioeconomy concepts (▶ <https://doi.org/10.1007/000-htc>)

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/978-3-032-09098-0_2. 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.

© The Author(s) 2026

I. Lewandowski et al. (eds.), *Bioeconomy*, https://doi.org/10.1007/978-3-032-09098-0_2

Contents

2.1 The Origin of the Concept of the Bioeconomy – 21

- 2.1.1 The First Use of the Terms 'Bioeconomics' and 'Bioeconomy' – 21
- 2.1.2 The Development of the Concept of the 'Knowledge-Based Bioeconomy' in the European Union – 22

2.2 The Rise of the Bioeconomy as a Global Concept – 25

- 2.2.1 USA – 25
- 2.2.2 Latin America and the Caribbean – 26
- 2.2.3 Asia – 27
- 2.2.4 Africa – 27
- 2.2.5 International Organizations – 27
- 2.2.6 Global Bioeconomy Summits – 27

2.3 Evolving Perspectives on the Bioeconomy – 28

- 2.3.1 Overview of Different Perspectives – 28
- 2.3.2 Early Perspectives: Resource Substitution and Biotechnology Innovation – 29
- 2.3.3 Criticism Against the Early Perspectives – 31
- 2.3.4 'Greening' the Bioeconomy – 33

2.4 Conclusion – 40

References – 41

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, ‘Enriquez never seems to have used the term “bioeconomy”—only “biotechnomy” 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

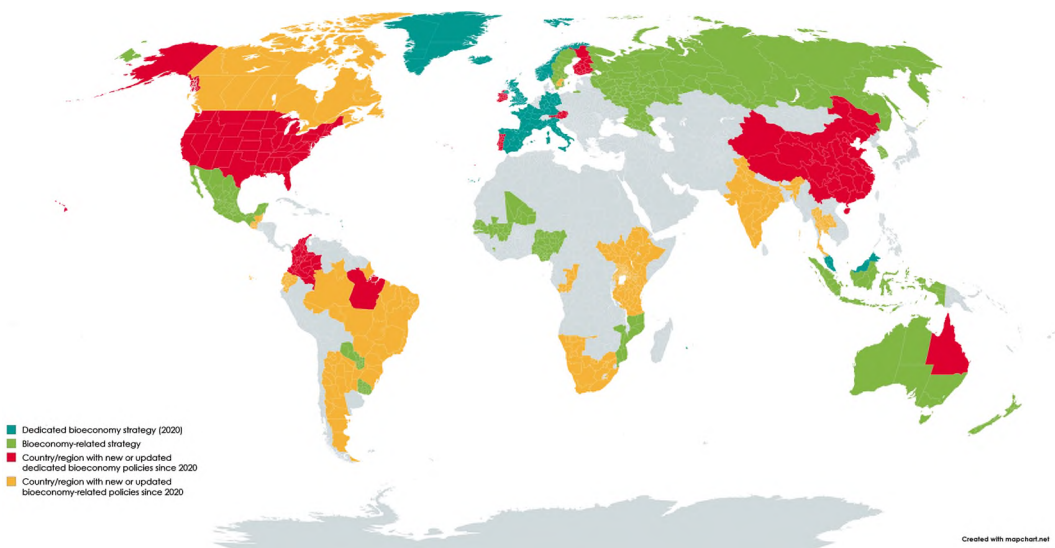
The EU is not the only region of the world where the concept of the bioeconomy has been promoted since the early 2000s. As shown in the following, the first decades of the twenty-first century saw the rise of the bioeconomy as a global concept. As of 2024, more than 60 countries had dedicated or related 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 the ‘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 bio-manufacturing 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 Caribbean) 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 communiqués, 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 communiqué 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 industrial-

ized 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 Bioeconomy

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 Commission⁷ 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).

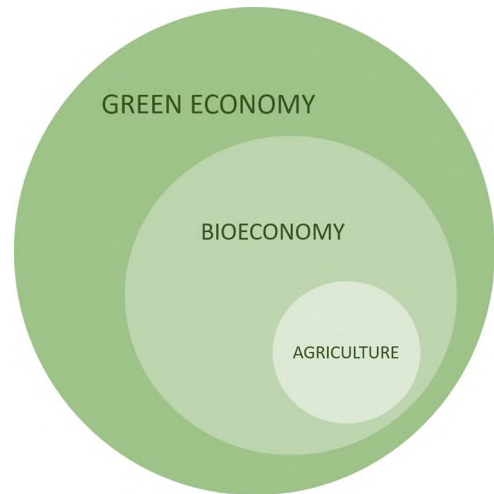
2

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).

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-



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

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-

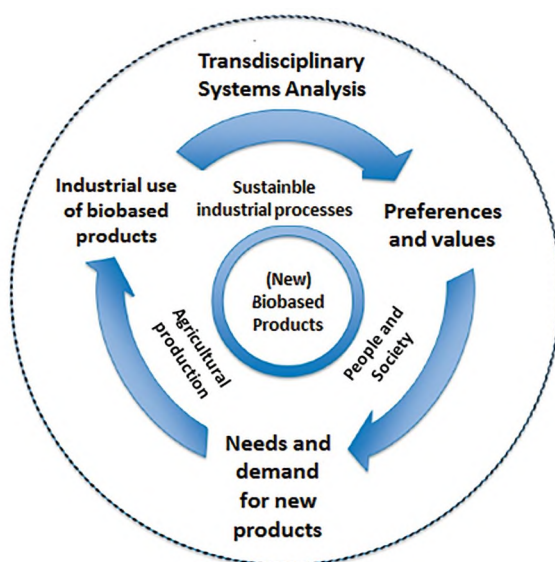
tribute to biodiversity conservation. This bottom-up perspective is rooted in forest regions of Latin America. Importantly, this perspective integrates the relations between two main elements: biological diversity and socio-cultural diversity. The term ‘socio-biodiversity’ has been coined to capture 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 Queiroz-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 transdisci-

plinary 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

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.

References

- Al-Ghanayem AA, Joseph B (2020) Current prospective in using cold-active enzymes as eco-friendly detergent additive. *Appl Microbiol Biotechnol* 104(7):2871–2882. <https://doi.org/10.1007/s00253-020-10429-x>
- Aramendis RH, Rodriguez AG, Krieger Merico LF (2018) Contribuciones a un gran impulso ambiental en América Latina y el Caribe: bioeconomía. Documentos de Proyectos. Economic Commission for Latin America and the Caribbean (ECLAC). <https://repositorio.cepal.org/server/api/core/bitstreams/a5bb120f-925a-4d8d-bcf4-68883a44d6b0/content>. Accessed Dec 16 2025
- Backhouse M (2021) Global inequalities and extractive knowledge production in the bioeconomy. In: Backhouse M et al (eds) *Bioeconomy and global inequalities*. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-030-68944-5_2
- Backhouse M, Lüthmann M, Tittor A (2022) Global inequalities in the bioeconomy: thinking continuity and change in view of the global soy complex. *Sustainability* 14(9):5481. <https://doi.org/10.3390/su14095481>
- Bailey I, Caprotti F (2014) The green economy: functional domains and theoretical directions of enquiry. *Area* 46(8):211–219. <https://doi.org/10.1068/a130102p>
- Barben D, Birner R, Zinke H (2021) Nachhaltige Bioökonomie und gesellschaftliche Transformation: Manifest mit zehn Thesen. GAIA - Ecol Perspect Sci Soc 30(1):12–17. <https://doi.org/10.14512/gaia.30.1.4>
- Bardi U (2009) Peak oil: the four stages of a new idea. *Energy* 34(3):323–326. <https://doi.org/10.1016/j.energy.2008.08.015>
- Bastos Lima MG (2021) Corporate power in the bioeconomy transition: the policies and politics of conservative ecological modernization in Brazil. *Sustainability* 13(12):6952. <https://doi.org/10.3390/su13126952>
- Bastos Lima MG, Palme U (2022) The bioeconomy–biodiversity Nexus: enhancing or undermining nature’s contributions to people? *Conservation* 2(1):7–25. <https://doi.org/10.3390/conservation2010002>
- Baumeister C, Kilian L (2016) Forty years of oil price fluctuations: why the price of oil may still surprise us. *J Econ Perspect* 30(1):139–160. <https://doi.org/10.1257/jep.30.1.139>
- Bioeconomy Summit (2015) Communiqué of the Global Bioeconomy Summit 2015: making bioeconomy work for sustainable development, Berlin
- Birch K (2006) The neoliberal underpinnings of the bioeconomy: the ideological discourses and practices of economic competitiveness. *Genom Soc Policy* 2(3):1–15. <https://doi.org/10.1108/00242530610667558>
- Birch K, Levidow L, Papaioannou T (2010) Sustainable capital? The Neoliberalization of nature and knowledge in the European “Knowledge-based Bioeconomy”. *Sustainability* 2(9):2898–2918. <https://doi.org/10.3390/su2092898>
- BMBF (2010) National Research Strategy BioEconomy 2030- Our Route towards a Biobased Economy. Federal Ministry of Education and Research (BMBF), Berlin
- BMBF (2014) Wegweiser Bioökonomie. Bundesministerium für Bildung und Forschung (BMBF). Federal Ministry of Education and Research, Berlin
- BMBF (2020) Nationale Bioökonomiestrategie. Bundesministerium für Bildung und Forschung (BMBF). Federal Ministry of Education and Research, Berlin
- BMEL (2014) National Policy Strategy on bioeconomy - renewable resources and biotechnological processes as a basis for food industry and energy: Federal Ministry of Food and Agriculture in Germany (BMEL), Berlin
- Bonaiuti M (2014) Bio-economics. In: D’Alisa G, Dematia F, Kallis G (eds) *Degrowth: a vocabulary for a new era*. Routledge Taylor & Francis Group, Abingdon Oxon, pp 52–55
- BÖR (2010) Bio-economy Council report 2010: bioeconomy innovation. German Bioeconomy Council (Bioökonomierat - BÖR), Berlin
- BÖR (2015a) Bioeconomy policy (Part II)—Synopsis of National Strategies around the World German Bioeconomy Council (Bioökonomierat - BÖR), Berlin

- 2
- BÖR (2015b) Global bioeconomy summit conference report—for a global sustainable bioeconomy. German Bioeconomy Council (Bioökonomierat - BÖR), Berlin
- Boulding KE (1966) The economics of the coming spaceship earth - environmental quality in a growing economy. In: Jarrent H (ed) Essays from the sixth resources for the future forum on environmental quality in a growing economy. Johns Hopkins University Press, Baltimore, pp 3–14
- Bugge MM, Hansen T, Klitkou A (2016) What is the bioeconomy? A review of the literature. *Sustainability* 8(7):691. <https://doi.org/10.3390/su8070691>
- Costa FA, Ciasca BS, Castro ECC, Barreiros RMM, Folhes R, Bergamini LL, Sobrino AS, Cruz A, Costa A, Simoes J, Almeida J, Souza HM (2020) Bioeconomy in the State of Pará. *Ocio-Biodiversity*. <https://doi.org/10.18235/0003713>
- Dauvergne P, Neville KJ (2010) Forests, food, and fuel in the tropics: the uneven social and ecological consequences of the emerging political economy of biofuels. *J Peasant Stud* 37(3):613–660. <https://doi.org/10.1080/03066150.2010.52451>
- de Gorter H, Drabik D, Just DR (2013) How biofuels policies affect the level of grains and oilseed prices: theory models and evidence. *Glob Food Sec* 2(2):82–88
- de Queiroz-Stein G, Siegel KM (2023) Possibilities for mainstreaming biodiversity? Two perspectives on the concept of bioeconomy. *Earth Syst Go* 17:100181. <https://doi.org/10.1016/j.esg.2023.100181>
- de Queiroz-Stein G, Martinelli FS, Dietz T, Siegel KM (2023) Disputing the bioeconomy-biodiversity nexus in Brazil: coalitions, discourses and policies. *For Policy* 2023:103101. <https://doi.org/10.1016/j.forpol.2023.103101>
- Dolge K, Balode L, Laktuka K, Kirsanovs V, Barisa A, Kubule A (2023) A comparative analysis of bioeconomy development in European Union countries. *Environ Manag* 71(2):215–233 <https://doi.org/10.1007/s00267-022-01751-3>
- EAC (2022) EAC Regional Bioeconomy Strategy. The State of The Bioeconomy in eastern Africa. https://easteco.org/policy_strategy/eac-regional-bioeconomy-strategy/. Accessed Dec 16, 2025
- EC (2005) New Perspectives on the Knowledge-Based Bio-Economy - Conference Report. European Commission (EC), Brussels
- EC (2012) Bioeconomy strategy ‘Innovating for sustainable growth - A bioeconomy for Europe’. <https://op.europa.eu/en/publication-detail/-/publication/1f0d8515-8dc0-4435-ba53-9570e47dbd51>
- EC (2013) Horizon 2020 - the EU Framework Programme for research and innovation. European Commission, Brussels
- EC (2018a) Communication COM/2018/673: a sustainable Bioeconomy for Europe: Strengthening the connection between economy, society and the environment. https://knowledge4policy.ec.europa.eu/publication/sustainable-bioeconomyeuropestrengthening-connection-between-economy-society_en. Accessed Dec 16 2025
- EC (2018b) The European way to use our natural resources: action plan. https://knowledge4policy.ec.europa.eu/publication/bioeconomy-european-way-use-ournatural-resources-action-plan-2018_en. Accessed Dec 16 2025
- EC (2021) Horizon Europe, the EU Research and Innovation Programme (2021–27): For a Green, Healthy, Digital and Inclusive Europe. EU Directorate-General for Research and Innovation, European Commission, Brussels. <https://data.europa.eu/doi/10.2777/601756>
- EC (2022) Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions: EU Bioeconomy Strategy Progress Report - European Bioeconomy Policy: Stocktaking and Future Developments. COM/2022/283 final. https://ec.europa.eu/info/sites/default/files/1_en_act_part1_v4.pdf. Accessed Dec 16 2025
- EC (2024) Communication from the Commission, The European Green Deal to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Building the future with nature: Boosting Biotechnology and Biomanufacturing in the EU, COM/2024/137. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52024DC0137>. Accessed Dec 16 2025
- Enriquez J (1998) Genomics and the world’s economy. *Science* 281(5379):925–926. <https://doi.org/10.1126/science.281.5379.92>
- Enriquez J (2002) The biotechnology (1.0): a rough map of bio-data flow. Division of Research, Harvard Business School Working Paper No. 03–028, August 2002
- Erb K-H, Gingrich S (2022) Biomass—critical limits to a vital resource. *One Earth* 5(1):7–9. <https://doi.org/10.1016/j.oneear.2021.12.014>
- EU (2000) Lisbon European Council 23 and 24 March 2000 - Presidency Conclusions Council of the European Union Lisbon. Available at: http://www.consilium.europa.eu/en/uedocs/cms_data/docs/pressdata/en/ec/00100-r1.en0.htm. Accessed July 15 2017
- EU (2007) En route to the knowledge-based bioeconomy (‘Cologne Paper’) German Presidency of the Council of the European Union (EU), Cologne
- EU Bioeconomy Youth Ambassadors (2024) Bioeconomy Youth Vision. European Youth Portal. Bartmann R, Bertacchi S, Bifone M, Ciantar H, Cogley D, Dirdaite U, Escórcio R, Jögi K, Lázár J, Mrozinski O, Nachtergaele P, Schabert P, Sciotti C, Werl C, Zaitseva D. European Union. https://youth.europa.eu/get-involved/sustainable-development/whats-youth-vision-bioeconomy_en. Accessed Dec 16 2025
- European Commission (2019a) Communication from the Commission, The European Green Deal. https://knowledge4policy.ec.europa.eu/publication/sustainable-bioeconomyeuropestrengthening-connection-between-economy-society_en. Accessed Dec 16 2025

- eur-lex.europa.eu/legalcontent/EN/TXT/?uri=COM%3A2019%3A640%3AFIN. Accessed Dec 16 2025
- European Commission (2019b) Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, and the Committee of the Regions: The European Green Deal. <https://www.kowi.de/Portaldata/2/Resources/fp/2019-com-european-green-deal-communication.pdf>. Accessed Dec 16 2025
- European Commission (EC) 2025. COM (2025) 960 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Strategic Framework for a Competitive and Sustainable EU Bioeconomy. Brussels, 27.11.2025 https://environment.ec.europa.eu/publications/bioeconomy-strategy_en (accessed 3.12.2025)
- Eversberg D, Holz J, Pungas L (2023) The bioeconomy and its untenable growth promises: reality checks from research. *Sustain Sci* 18(2):569–582. <https://doi.org/10.1007/s11625-022-01237-5>
- FAO (2024) Bioeconomy for sustainable food and agriculture: a global opportunity. Position Paper. FAO, Rome, Italy. ISBN 978-92-5-139032-0
- Fleischmann BM, Mayer A, Görg C, Pichler M (2024) Negotiating biophysical limits in the European Union's bioeconomy: a critical analysis of two conflicts over regulating biomass use in EU policy. *Sustain Sci* 19(6):1935–1948. <https://doi.org/10.1007/s11625-024-01543-0>
- Gawel E, Pannicke N, Hagemann N (2019) A path transition towards a bioeconomy—the crucial role of sustainability. *Sustainability* 11(11):3005. <https://doi.org/10.3390/su11113005>
- GBS Communique (2018) Communiqué: International Bioeconomy Forum 2018. Available at: <https://www.bioekonomierat.de/media/pdf/archiv/international-gbs-2018-communique.pdf>. Accessed Dec 16 2025
- GBS Communique (2024) Communiqué: International Advisory Council of the Global Bioeconomy Summit 2024. Available at: <https://gbs2024.org/wp-content/uploads/2024/10/IACGB-Communique-24October2024.pdf>. Accessed Dec 16 2025
- GBS24 (2024) Global Bioeconomy Summit. <https://gbs2024.org/>. Accessed 11 Jan 2024
- Geoghegan-Quinn M (2013) Role of research and innovation in agriculture. Speech at the European Parliament on June 4 2013, Brussels
- Ghisellini P, Cialani C, Ulgiati S (2016) A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *J Clean Prod* 114:11–32. <https://doi.org/10.1016/j.jclepro.2015.09.007>
- Glatzel K, Virchow D, Nakitto AMS, Niyonsenga S, Babu S, Srivastava N, Kashandula P (2024) Bioeconomy pathways: experience from Africa, Asia, and Latin America. Chapter 9. In: Tadesse G, Glatzel K, Savadogo M (eds) 2024 ReSAKSS Annual Trends and Outlook Report, Advancing the climate and bioeconomy agenda in Africa for resilient and sustainable agrifood systems. AKADEMIYA 2063 and International Food Policy Research Institute. <https://doi.org/10.54067/9798991636902>
- Glick JL (1982) The industrial impact of the biological revolution. *Technol Soc* 4(4):283–293. [https://doi.org/10.1016/0160-791X\(82\)90005-7](https://doi.org/10.1016/0160-791X(82)90005-7)
- Gottwald F-T, Budde J (2015) Mit Bioökonomie die Welt ernähren? Institut für Welternährung – World Food Institute e.V., Berlin
- Gottwald FT (2016) Bioeconomy - a challenge to integrity. In: Westra L, Gray J, D'Aloia A (eds) The common good and ecological integrity: human rights and the support of life. Earthscan/Routledge, London/New York, pp 22–35
- Hausknost D, Schriebl E, Lauk C, Kalt G (2017) A transition to which bioeconomy? An exploration of diverging techno-political choices. *Sustainability* 9(4):669. <https://doi.org/10.3390/su9040669>
- Headey D, Fan S (2008) Anatomy of a crisis: the causes and consequences of surging food prices. *Agric Econ* 39(SUPPL. 1):375–391. <https://doi.org/10.1111/j.1574-0862.2008.00345.x>
- Hodson de Jaramillo E, Henry G, Trigo E (2019) La bioeconomía: Nuevo marco para el crecimiento sostenible en América Latina. https://repository.javeriana.edu.co/bitstream/handle/10554/43705/Bioeconom%C3%ada_WEB.pdf?sequence=2&isAllowed=y. Accessed Dec 16 2025
- Hoff H, Johnson FX, Allen B, Biber-Freudenberger L, Förster JJ (2018) Sustainable bio-resource pathways towards a fossil-free world: the European bioeconomy in a global development context. In: Institute for European Environmental Policy (IEEP), Brussels
- Hölscher K, Wittmayer JM, Loorbach D (2018) Transition versus transformation: what's the difference? *Environ Innov Soc Trans* 27:1–3. <https://doi.org/10.1016/j.eist.2017.12.003>
- IACGB (2015) Communiqué: making bioeconomy work for sustainable development. Available at: https://gbs2015.com/fileadmin/gbs2015/Downloads/Communique_final_neu.pdf. Accessed Dec 15 2025
- IACGB (2020) Global Bioeconomy Policy Report (IV): a decade of bioeconomy policy development around the world. International Advisory Council on Global Bioeconomy. https://gbs2020.net/wp-content/uploads/2021/04/GBS-2020_Global-Bioeconomy-Policy-Report_IV_web-2.pdf. Accessed Dec 16 2025
- IACGG (2024) Bioeconomy globalization: Recent trends and drivers of national programs and Policies. International Advisory Council on Global Bioeconomy. Available from: https://www.iacgb.net/lw_resource/datapool/systemfiles/elements/files/52440fb0-f35d-11ee-9ed1-dead53a91d31/current/document/Global_Bioeconomy_-_Apr_2024_IACGB.pdf. Accessed Dec 16 2025

- Johnson FX, Canales N, Fielding M, Gladkykh G, Aung MT, Bailis R (2022) A comparative analysis of bioeconomy visions and pathways based on stakeholder dialogues in Colombia, Rwanda, Sweden, and Thailand. *J Environ Policy Plan* 24(5):680–700. <https://doi.org/10.1080/1523908X.2022.2037412>
- Kalkuhl M, von Braun J, Torero M (2016) Volatile and extreme food prices food security and policy: an overview. In: Kalkuhl M, von Braun J, Torero M (eds) *Food price volatility and its implications for food security and policy*. Springer Open, pp 3–31
- Loiseau E, Saikku L, Antikainen R et al (2016) Green economy and related concepts: an overview. *J Clean Prod* 139:361–371. <https://doi.org/10.1016/j.jclepro.2016.08.024>
- Lühmann M, Vogelpohl T (2023) The bioeconomy in Germany: a failing political project? *Ecol Econ* 207:107783. <https://doi.org/10.1016/j.ecolecon.2023.107783>
- Mann CC (2018) *The Wizard and the Prophet—science and the future of our planet*. Picador, London
- Merriam-Webster (2024) *Bioecology*. <https://www.merriam-webster.com/dictionary/bioecology>. Accessed 11 Dec 2024
- Meyer R (2017) Bioeconomy strategies: contexts, visions, guiding implementation principles and resulting debates. *Sustainability* 9(6):1031. <https://doi.org/10.3390/su9061031>
- Ministerio de Ciencia, Tecnología e Innovación (2020) *Bioeconomía para un Crecimiento Sostenible*. https://minciencias.gov.co/sites/default/files/upload/paginas/bioeconomia_para_un_crecimiento_sostenible-qm_print.pdf. Accessed Dec 16 2025
- Ministério do Desenvolvimento, Indústria, Comércio e Serviços (MDIC). Governo Federal lança a Estratégia Nacional de Bioeconomia. Accessed on 29th Nov 2024. <https://www.gov.br/mdic/pt-br/assuntos/noticias/2024/junho/governo-federal-lanca-a-estrategia-nacional-de-bioeconomia>. Accessed Dec 16 2025
- Muscat A, de Olde EM, Ripoll-Bosch R, Van Zanten HHE, Metz TAP, Termeer CJAM, van Ittersum MK, de Boer IJM (2021) Principles, drivers and opportunities of a circular bioeconomy. *Nat Food* 2:561–566. <https://doi.org/10.1038/s41574-021-00387-7>
- O'Brien M, Schütz H, Bringezu S (2015) The land footprint of the EU bioeconomy: monitoring tools, gaps and needs. *Land Use Policy* 47:235–246. <https://doi.org/10.1016/j.landusepol.2015.04.012>
- OECD (2004) *Biotechnology for sustainable growth and development*. OECD, Paris
- Ollinaho J, Köger H (2023) Separating the two faces of 'Bioeconomy': plantation economy and sociobiodiverse economy in Brazil. *Forest Policy and Economics* 149: 102932
- Patermann C, Aguilar A (2018) The origins of the bioeconomy in the European Union. *New Biotechnol* 40:20–24. <https://doi.org/10.1016/j.nbt.2017.04.002>
- Pearce DW, Turner KR (1989) *Economics of natural resources and the environment*. Johns Hopkins University Press, Baltimore
- Pollution Probe (2002) *Towards a biobased economy—issues and challenges*. Pollut Probe, Toronto
- Potočník J (2005) Transforming life sciences knowledge into new sustainable eco-efficient and competitive products. Speech held at the conference on knowledge-based bio-economy Brussels 15 September 2005 at the European Commission Brussels
- Ribeiro SM, Jardim HL, de Azevedo UR, Coelho V, Bachie LS, Soares-Filho B (2020) Non-Timber Forest Products (NTFP) in the Brazilian Amazon and Cerrado Biomes: Multi-Scale Governance for Implementing Enhanced Socio-Biodiversity Chains. *Sustainability in Debate* 11(2):42–61
- Rodríguez AG, Rodrigues M, Sotomayor O (2019) Towards a sustainable bioeconomy in Latin America and the Caribbean: elements for a regional vision. Economic Commission for Latin America and the Caribbean (ECLAC)
- Salvador R, Barros MV, Freire F, Halog A, Piekarski CM, De Francisco AC (2021) Circular economy strategies on business modelling: identifying the greatest influences. *J Clean Prod* 229:126918. <https://doi.org/10.1016/j.jclepro.2021.126918>
- Saes MSM, Saes BM, Feitosa ERM, Poschen P, Val AL, Marcovitch J (2023) When do supply chains strengthen biological and cultural diversity? Methods and indicators for the socio-biodiversity bioeconomy. *Sustainability* 15(10):Article 10. <https://doi.org/10.3390/su15108053>
- Sarmiento Barletti JP, Monterroso I, Atmadja S (2021) Lessons on social inclusion for transformative forest-based bioeconomy solutions. <https://doi.org/10.17528/cifor/008272>
- Scheiterle L, Ulmer A, Birner R et al (2018) From commodity-based value chains to biomass-based value webs: the case of sugarcane in Brazil' s bioeconomy. *J Clean Prod*. <https://doi.org/10.1016/j.jclepro.2017.05.150>
- Sengupta P, Choudhury BK, Mitra S, Agrawal KM (2019) Low carbon economy for sustainable development. In: Reference module in materials science and materials engineering. <https://doi.org/10.1016/B978-0-12-803581-8.11217-2>
- Siegel KM, Deciancio M, Kefeli D, de Queiroz-Stein G, Dietz T (2022) Fostering transitions towards sustainability? The politics of bioeconomy development in Argentina, Uruguay, and Brazil. *Bull Lat Am Res* 41(2):222–238. <https://doi.org/10.1111/blar.13353>
- Sinkko T, Sanyé-Mengual E, Corrado S, Giuntoli J, Sala S (2023) The EU Bioeconomy Footprint: using life cycle assessment to monitor environmental impacts of the EU Bioeconomy. *Sustain Prod Consump* 37:169–179. <https://doi.org/10.1016/j.spc.2023.02.015>
- Trigo EJ, Henry G, Sanders J, Schurr U, Ingelbrecht I, Revel C, Santana C, Roch P (2013) Towards bio-

- economy development in Latin America and the Caribbean. Available at: https://agritrop.cirad.fr/567934/1/document_567934.pdf
- UN (1992) Agenda 21. United Nations Conference on Environment and Development Rio de Janeiro Brazil 3 to 14 June 1992. Available at: <https://sustainabledevelopment.un.org/outcomedocuments/agenda21>. Accessed 15 July 2017
- UN (2012) The future we want. Resolution adopted by the General Assembly United Nations Sixth Session 22 September 2012 A/Res/66/288
- UNEP (2011) Toward and poverty eradication. United Nations Environment Programme (UNEP). www.unep.org/greeneconomy. Accessed 15 July 2017
- Urmetzer S, Lask J, Vargas-Carpintero R, Pyka A (2020) Learning to change: transformative knowledge for building a sustainable bioeconomy. *Ecol Econ* 167:106435. <https://doi.org/10.1016/j.ecolecon.2019.106435>
- van der Veen S, Asveld L, Osseweijer P (2024) Designing bio-based value chains for social justice: the potential of Capability Sensitive Design. *Energy Res Soc Sci* 117:103724. <https://doi.org/10.1016/j.erss.2024.103724>
- Vogt W (1948) Road to survival. William Sloane Associates, New York
- von Braun (2014) Bioeconomy and sustainable development – dimensions. *Rural* 21(2):6–9
- WCED (1987) Our Common Future. World Commission on Environment and Development (WCED). Oxford University Press, Oxford
- White House (2012) National Bioeconomy Blueprint, Washington DC
- White House (2022) Executive order on advancing biotechnology and biomanufacturing innovation for a sustainable, safe, and secure American bioeconomy, Washington DC
- World Bank (2023) Unleashing opportunities for the bioeconomy in the mountain regions of Romania. Reimbursable Advisory Services Agreement on Romania Mountain Area Development World Bank, Washington, DC
- WWF (2009) Industrial biotechnology - more than green fuel in a dirty economy? World Wide Fund for Nature (WWF) Denmark, Copenhagen
- Zink T, Geyer R (2017) Circular economy rebound. *J Ind Ecol* 21(3):593e602. <https://doi.org/10.1111/jiec.12545>

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.



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>)

Contents

- 3.1 Sustainability and Multidimensionality – 50
- 3.2 Multifunctionality – 53
- 3.3 Circularity and Cascading Resource Use – 57
- 3.4 Inter- and Transdisciplinarity – 61
- 3.5 A Holistic Systems Thinking Approach in the Bioeconomy – 64
- References – 69

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/978-3-032-09098-0_3. 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.

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

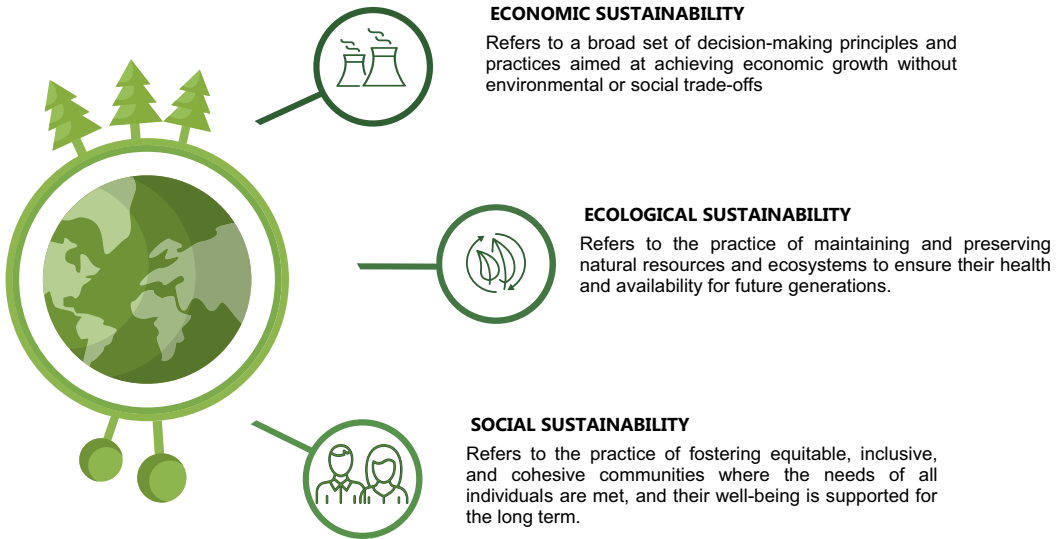
The concept of sustainability in the context of productive economic systems has its origins in forestry—to preserve the value of the forest and ensure its future usability: only as many trees should be felled as can grow back. Translated into an overall concept this means that sustainability aims to 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 effectively 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).

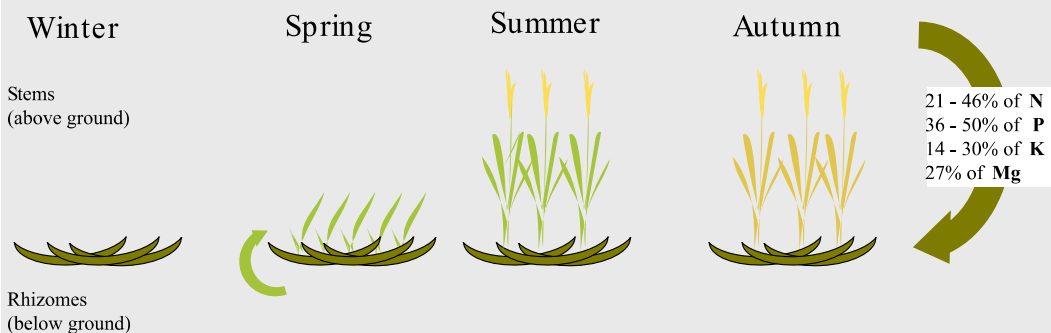
Miscanthus is widely used for bioenergy production. Its biomass can be burned directly or co-fired with coal to produce electricity and heat. For energy purposes, miscanthus biomass is either harvested dry in early spring, after plant nutrients have been translocated to the rhizomes, or harvested green 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 CO₂ 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 CO₂ 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

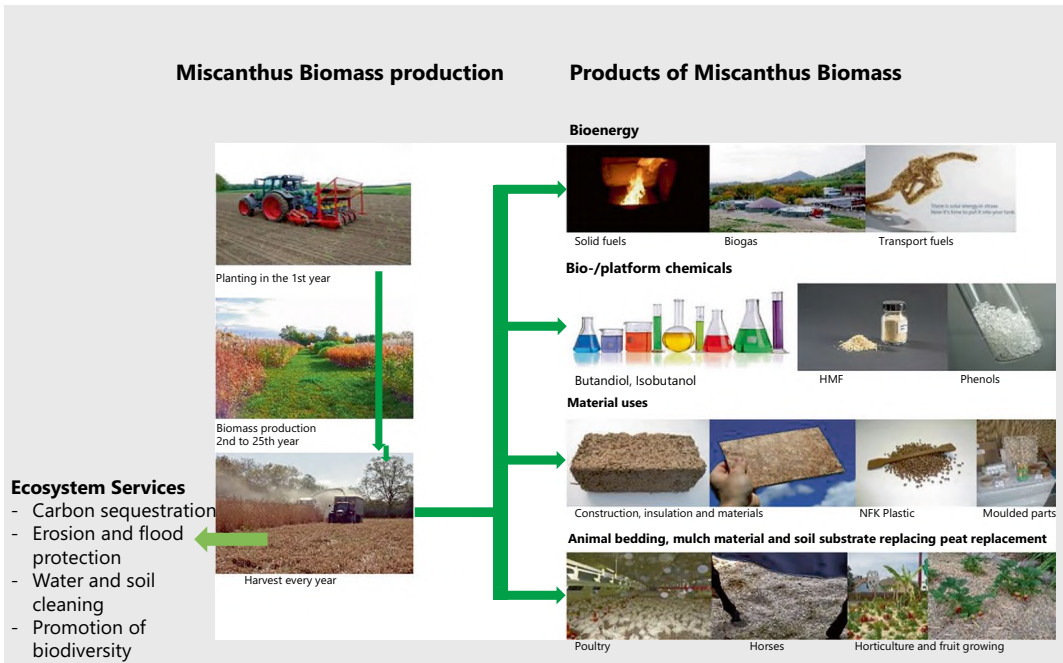


Fig. 3.4 Miscanthus delivers biomass for multiple bio-based products simultaneously with different ecosystem services

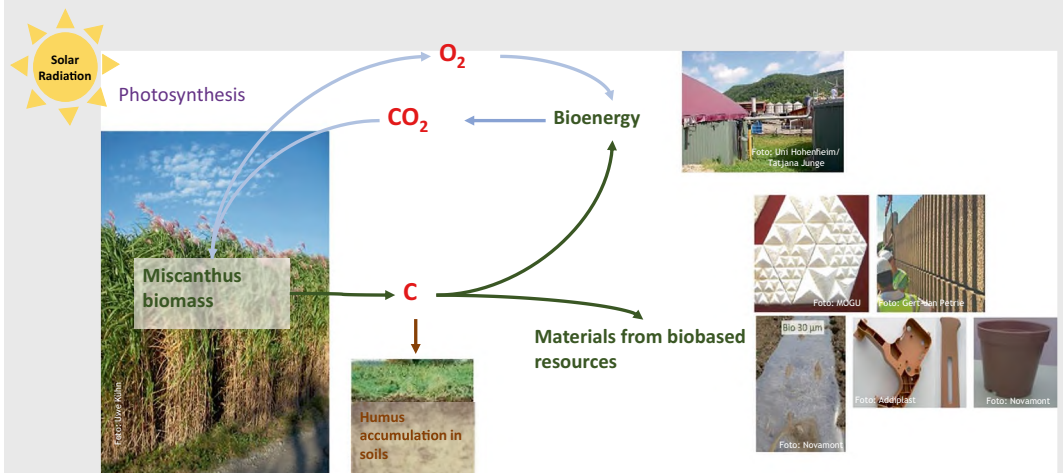


Fig. 3.5 How miscanthus biomass production delivers biomass for different products and reduces atmospheric CO_2 at the same time

- 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 (Zukunftagentur 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 evi-

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).

dent in a bioeconomy, where the circular flow extends to biological resources and nutrients.

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 addi-

tional 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

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).

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.

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

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).

minimizing waste and emissions from the processing and conversion of products (see ► Chap. 17).

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).

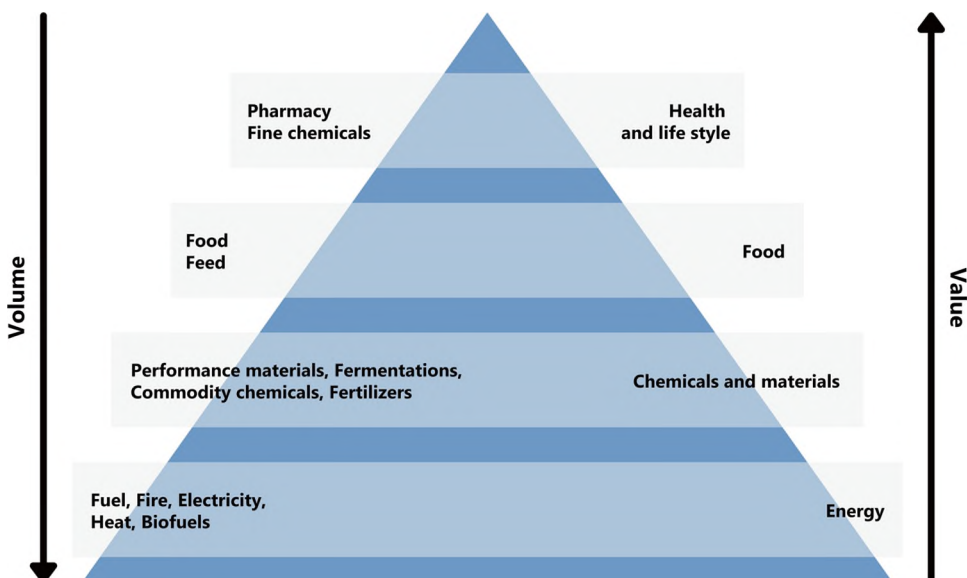


Fig. 3.6 Bio-products value pyramid

► **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 required of the fertilizers produced in the biorefineries (quantity, properties, quality criteria and composition) 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

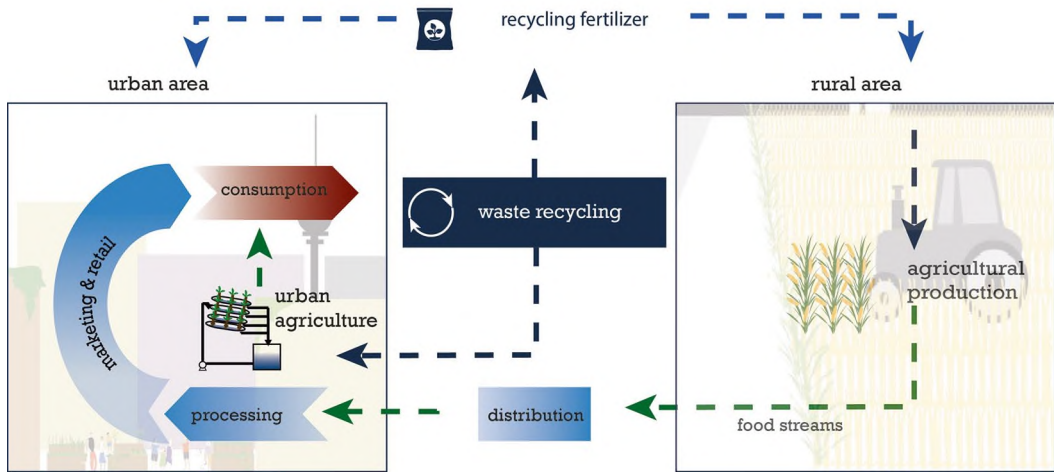


Fig. 3.7 Schematic illustration of the closed loop of agricultural waste and residue streams to produce recycling fertilizer for agricultural processes in urban and rural areas. (© Marielle Trenkner)

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 plu-

rality 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 scientific 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 through 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 configured 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, policy-makers, 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

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

(Darnhofer 2021).

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.

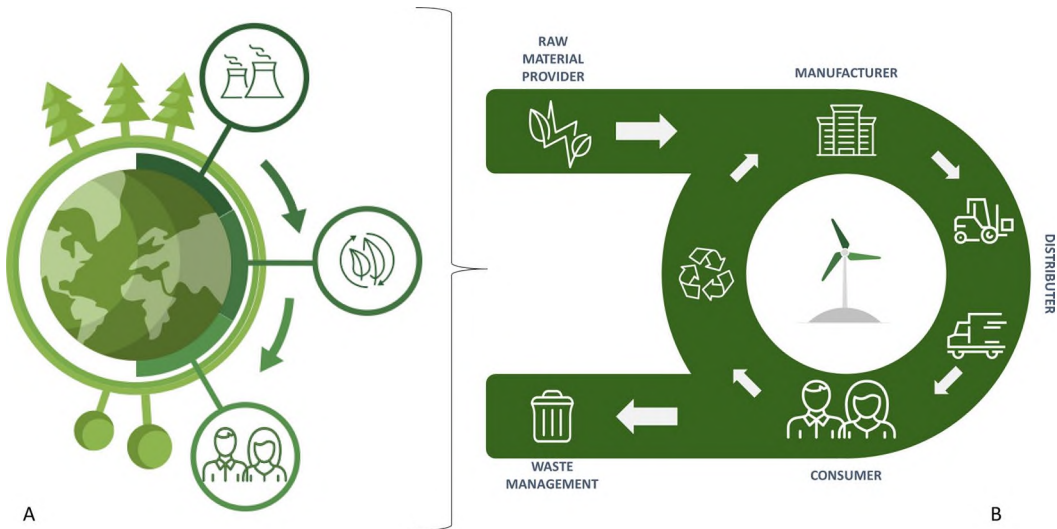


Fig. 3.8 Bioeconomy systems are embedded in a larger (regionally specific) context: **a** on a global scale via dispersed biomass production systems, and **b** at the local level through value chain components and actors

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 processes 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 economic 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 support 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.

References

- Blomsma F, Brennan, G (2017) The emergence of circular economy: a new framing around prolonging resource productivity. *J Indus Ecol* 21(3):603–614. <https://doi.org/10.1111/jiec.2017.21.issue-3>, <https://doi.org/10.1111/jiec.12603>
- Bracco S, Tani A, Çalicioğlu Ö, Gomez San Juan M, Bogdanski A (2019) Indicators to monitor and evaluate the sustainability of bioeconomy: overview and a proposed way forward Environment and Natural Resources Management Working Paper, vol 77, 1st edn. Food and Agriculture Organization of the United Nation, Rome, Italy. ISBN 978-92-5-131796-9
- Brand F (2009) Critical natural capital revisited: ecological resilience and sustainable development. *Ecol Econ* 68(3):605–612. <https://doi.org/10.1016/j.ecolecon.2008.09.013>
- Bringezu S, Banse M, Ahmann L, Bezama NA, Billig E, Bischof R, Blanke C, Brosowski A, Brüning S, Borchers M, Budzinski M, Cyffka K-F, Distelkamp M, Egenolf V, Flaute M, Geng N, Gieseking L, Graß R, Hennenberg K, Hering T, Iost S, Jochem D, Krause T, Lutz C, Machmüller A, Mahro B, Majer S, Mantau U, Meisel K, Moesenfechtel U, Noke A, Raussen T, Richter F, Schaldach R, Schweinle J, Thrän D, Uglik M, Weimar H, Wimmer F, Wydra S, Zeug W (2020) *Pilotbericht zum Monitoring der deutschen Bioökonomie* Center for Environmental Systems Research (CESR). Universität Kassel, Kassel. <https://doi.org/10.17170/kobra-202005131255>
- Brown BJ, Hanson ME, Liverman DM, Merideth RW (1987) Global sustainability: toward definition. *Environ Manag* 11(6):713–719. <https://doi.org/10.1007/BF01867238>
- Campbell-Johnston K, Vermeulen WJV, Reike D, Brullot S (2020) The circular economy and cascading: towards a framework. *Resour Conserv Recycl* X 7100038. <https://doi.org/10.1016/j.rcrx.2020.100038>
- Carrez D, Van Leeuwen P (2015) Bioeconomy: circular by nature. *Eur Files* 38:34–35
- Carus M, Dammer L (2018) The circular bioeconomy—concepts, opportunities, and limitations. *Indus Biotechnol* 14(2):83–91
- Cascio J (2009) Resilience. *Foreign Policy* 172:92
- Cherubini F (2010) The biorefinery concept: using biomass instead of oil for producing energy and chemicals. *Energy Convers Manag* 51:1412–1421. <https://doi.org/10.1016/j.enconman.2010.01.015>
- Corvellec H, Stowell AF, Johansson N (2022) Critiques of the circular economy. *J Ind Ecol* 26(2):421–432. <https://doi.org/10.1111/jiec.13187>
- D'Amato D, Droste N, Allen B, Kettunen M, Lähinen K, Korhonen J, Leskinen P, Matthies BD, Toppinen A (2017) Green, circular, bio economy: a comparative analysis of sustainability avenues. *J Clean Prod.* Elsevier Ltd 168:716–734
- Darnhofer I (2021) Resilience or how do we enable agricultural systems to ride the waves of unexpected change? *Agric Syst* 187:102997. <https://doi.org/10.1016/j.agsy.2020.102997>
- De Besi M, McCormick K (2015) Towards a bioeconomy in Europe: national, regional and industrial strategies. *Sustainability* 7(8):10461–10478
- Diaz-Chavez R, Mortensen S, Wikman A (2020) Bioeconomy: tapping natural and human resources to achieve sustainability. Available at: <https://www.sei.org/publications/bioeconomy-natural-human-resources-sustainability>
- Dietz T, Börner J, Förster JJ, von Braun J (2018) Governance of the bioeconomy: a global comparative study of national bioeconomy strategies. *Sustainability* 10(9):3190
- Egenolf V, Bringezu S (2019) Conceptualization of an indicator system for assessing the sustainability of the bioeconomy. *Sustainability* 11(2):443
- EU Bioeconomy Youth Ambassadors (2024) Bioeconomy Youth Vision. Bartmann R, Bertacchi S, Bifone M, Ciantar H, Cogley D, Dirdaite U, Escórcio R, Jögi K, Lázár J, Mrozinski O, Nachtergaele P, Schabert P, Sciotti C, Werl C, & Zaitseva D (2024). European Youth Portal, European Union. Available at: https://youth.europa.eu/get-involved/sustainable-development/whats-youth-vision-bioeconomy_en
- European Commission (2022) EU Bioeconomy Strategy Progress Report—European Bioeconomy policy: Stocktaking and future developments (COM(2022) 283 final)
- European Environmental Agency (2016) Circular economy in Europe — Developing the knowledge base. Available at: <https://www.eea.europa.eu/publications/circular-economy-in-europe>
- FAO (2018) Assessing the contribution of bioeconomy to countries economy: a brief review of national frameworks. Food and Agriculture Organization of the United Nation, Rome, Italy. ISBN 978-92-5-130603-1
- Fiksel J, Bakshi BR (2023) Designing for resilience and sustainability: an integrated systems approach. In: Bakshi BR (ed) *Engineering and ecosystems*. Springer International Publishing, pp 469–500. https://doi.org/10.1007/978-3-031-35692-6_21
- Friedrich J, Bunker I, Uthes S, Zscheischler J (2021) The potential of bioeconomic innovations to contribute to a social-ecological transformation: a case study in the livestock system. *J Agric Environ Ethics* 34:24. <https://doi.org/10.1007/s10806-021-09866-z>

- Fritsche U, Brunori G, Chiamonti D, Galanakis C, Hellweg S, Matthews R, Panoutsou C (2020) Future transitions for the bioeconomy towards sustainable development and a climate-neutral economy - knowledge synthesis final report. Publications Office of the European Union, Luxembourg
- Gawel E, Pannicke N, Hagemann N (2019) A path transition towards a bioeconomy—the crucial role of sustainability. *Sustainability* 11(11):3005
- Geissdoerfer M, Savaget P, Bocken NMP, Hultink EJ (2018) The circular economy—a new sustainability paradigm? *J Clean Prod* 143. <https://doi.org/10.1016/j.jclepro.2016.12.048>
- Giampietro M, Funtowicz SO (2020) From elite folk science to the policy legend of the circular economy. *Environ Sci Pol* 109:64–72. <https://doi.org/10.1016/j.envsci.2020.04.012>
- Götz M, Lask J, Lewandowski I, Kruse A (2023) Comparative LCA studies of simulated HMF biorefineries from maize and miscanthus as an example of first- and second-generation biomass as a tool for process development. *GCB Bioenergy* 15(8):n/a–n/a. <https://doi.org/10.1111/gcbb.13079>
- Haider MN, Liu C-G, Tabish TA et al (2022) Resource recovery of the wastewater-derived nutrients into algal biomass followed by its cascading processing to multiple products in a circular bioeconomy paradigm. *Fermentation* 8:650. <https://doi.org/10.3390/fermentation8110650>
- Hasenheit M, Gerdes H, Kiresiewa Z, Beekman V (2016) Summary report on the social, economic and environmental impacts of the bioeconomy. European Union
- Hirsch Hadorn GB, Pohl C (2010) Solving problems through transdisciplinary research. In: R Frodeman, JT Klein, C Mitcham (eds), *The Oxford Handbook of Interdisciplinarity*. Oxford, GB: Oxford University Press
- IPCC (2018) Summary for Policymakers. In: Masson-Delmotte V, P Zhai, H-O Pörtner, D Roberts, J Skea, PR Shukla, A Pirani, W Moufouma-Okia, C Péan, R. Pidcock, S. Connors, JBR Matthews, Y Chen, X Zhou, MI Gomis, E Lonnoy, T Maycock, M Tignor, and T Waterfield (eds) *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp 3–24. <https://doi.org/10.1017/9781009157940.001>
- Ison R (2012) Systems practice: making the systems in Farming Systems Research effective. In: Darnhofer I, Gibbon D, Dedieu B (eds) *Farming systems into the 21st century: the new dynamic*. Springer, Dordrecht, pp 141–157
- Kardung M, Cingiz K, Costenoble O, Delahaye R, Heijman W, Lovrić M, van Leeuwen M, M'barek R, van Meijl H, Piotrowski S, Ronzon T, Sauer J, Verhoog D, Verkerk PJ, Vrachlioli M, Wesseler JHH, Zhu BX (2021) Development of the circular bioeconomy: drivers and indicators. *Sustainability* 13(1):413
- Kiesel A, Lewandowski I (2017) Miscanthus as biogas substrate-cutting tolerance and potential for anaerobic digestion. *GCB Bioenergy* 9(1):153–167
- Kircher M (2021) Bioeconomy—present status and future needs of industrial value chains. *New Biotechnol* 60:96–104. <https://doi.org/10.1016/j.nbt.2020.09.005>
- Klauer B, Schindler H (2020) Nachhaltigkeit und Bioökonomie. In: Thrän D, Moesenfechter U (eds) *Das System Bioökonomie*. Springer, Berlin, pp 362–369
- Knierim A, Laschewski L, Boyarintseva O (2018) Inter- and Transdisciplinarity in the bioeconomy. In: Lewandowski I (ed) *Bioeconomy. Shaping the transition to a sustainable, biobased economy*. Springer, Switzerland, pp 39–72
- Lange S, Florian, Kern F, Peuckert J, Santarius T (2021) The Jevons paradox unravelled: a multi-level typology of rebound effects and mechanisms. *Energy Res Soc Sci* 74:101982. <https://doi.org/10.1016/j.erss.2021.101982>
- Lask J, Wagner M, Trindade LM, Lewandowski I (2018) Life cycle assessment of ethanol production from miscanthus: a comparison of production pathways at two European sites. *GCB Bioenergy* 11:269–288. <https://doi.org/10.1111/gcbb.12551>
- Lewandowski I, Clifton-Brown J, Kiesel A, Hastings A, Iqbal Y (2022) Miscanthus. In: Alexopoulou E (ed) *Perennial grasses for bioenergy and bioproducts*. Academic Press. <https://doi.org/10.1016/B978-0-12-812900-5.00002-3>
- Lewandowski I (2018) Context. In: Lewandowski I (ed) *Bioeconomy: shaping the transition to a sustainable, biobased economy, 1*. Springer/University of Hohenheim, Berlin/Heidelberg/Stuttgart
- Lewandowski I, von Cossel M, Winkler B, Bauerle A, Gaudet N, Kiesel A, Lewin E, Magenau E, Marting Vidaurre NA, Müller B, Schlecht V, Thumm U, Trenkner M, Vargas-Carpintero R, Weickert S, Weik J, Reinmuth E (2024) An adapted indicator framework for evaluating the potential contribution of bioeconomy approaches to agricultural systems resilience. *Adv Sustain Sys* 8(7). <http://doi.org/10.1002/adsu.v8.7>, <https://doi.org/10.1002/adsu.202300518>
- Locke H, Rockström J, Bakker P, Bapna M, Gough M, Hilty J, Lambertini M, Morris J, Polman P, Rodriguez CM, Samper C, Sanjayan M, Zabey E, Zurita P (2021) A nature-positive world: the global goal for nature. <https://www.naturepositive.org>
- McDonough W, Braungart M (2002) *Cradle to cradle: remaking the way we make things*. North Point Press.
- Muscat A, De Olde EM, Ripoll-Bosch R, Van Zanten HHE, Metz TAP, Termier CJAM, Van Ittersum MK, De Boer IJM (2021) Principles, drivers and

- opportunities of a circular bioeconomy. *Nat Food* 2(8):561–566
- Oneyali W, Schlaile MP, Winkler B (2023) Navigating the biocosmos: cornerstones of a bioeconomic Utopia. *Land* 12(6):1212. <https://doi.org/10.3390/land12061212>
- Pelenc J, Ballet J (2015) Strong sustainability, critical natural capital and the capability approach. *Ecol Econ* 112:36–44. <https://doi.org/10.1016/j.ecolecon.2015.02.006>
- Pfau SF, Hagens JE, Dankbaar B, Smits AJM (2014) Visions of sustainability in bioeconomy research. *Sustainability* 6(3):1222–1249
- Pohl C, Klein JT, Hoffmann S, Mitchell C, Fam D (2021) Conceptualising transdisciplinary integration as a multidimensional interactive process. *Environ Sci Pol* 118:18–26. <https://doi.org/10.1016/j.envsci.2020.12.005>
- Pyka A, Ari E, Alva-Ferrari A, Urmetzer S (2020) The bioeconomy transition process: sailing through storms and Doldrums in unknown waters. *J Innov Econ Manag* Prepublication:1110-27. <https://doi.org/10.3917/JIE.PR1.0110>
- Richardson K et al (2023) Earth beyond six of nine planetary boundaries. *Sci Adv* 9(37). <https://doi.org/10.1126/sciadv.adh2458>
- Rockström J, Steffen W, Noone K, Persson Å, Chapin III FS, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B, de Wit CA, Hughes T, van der Leeuw S, Rodhe H, Sörlin S, Snyder PK, Costanza R, Svedin U, Falkenmark M, Karlberg L, Corell RW, Fabry VJ, Hansen J, Walker B, Liverman D, Richardson K, Crutzen P, Foley JA (2009) A safe operating space for humanity. *Nature* 461(7263):472–475. <https://doi.org/10.1038/461472a>
- Santillo D (2007) Reclaiming the definition of sustainability (7 pp). *Environ Sci Pollut Res Int* 14(1):60–66. <https://doi.org/10.1065/espr2007.01.375>
- Schlaile MP, Friedrich J, Porst L, Zscheischler J (2025) Bioeconomy innovations and their regional embeddedness: results from a qualitative multiple-case study on German flagship innovations. *Prog Econ Geogr* 3(1):100044. <https://doi.org/10.1016/j.peg.2025.100044>
- Schiere JB, Groenland R, Vlug A, van Keulen H (2004) System thinking in agriculture: an overview. In: Rickert K (ed) *Emerging challenges for farming systems - lessons from Australian and Dutch agriculture*. Rural Industries Research and Development Corporation, Barton A.C.T
- Schindler D (2021) The Circular bioeconomy is on its way. Available at: https://www.goingpublic.de/wp-content/uploads/epaper/2021_4_LS/#8,
- Schipfer F, Burlì P, Fritsche U, Hennig C, Stricker F, Wirth M, Proskurina S, Serna-Loaiza S (2024) The circular bioeconomy: a driver for system integration. *Energy Sustain Soc* 14(1):34. <https://doi.org/10.1186/s13705-024-00461-4>
- Schmidt JC (2008) Towards a philosophy of interdisciplinarity. *Poiesis Prax* 5:53–69. <https://doi.org/10.1007/s12022-007-0037-8>
- Schultz FC, Valentinov V, Reinhardt RJ, Pies I (2024) The circular economy rebound effect: Reconceptualizing rebound approaches and mitigation opportunities from an ordonomic perspective. *J Indus Ecol* 28(3):374–385. <https://doi.org/10.1111/jiec.v28.3>, <https://doi.org/10.1111/jiec.13485>
- Schlecht V, Vargas-Carpintero R, Trenkner M, Duarte LM, von Ow-Wachendorf F, Lunetta R, Weik J (2024) Started from the bottom now we're here – a young researcher's perspective on the bioeconomy youth vision. *EFB Bioecon J* 4100072. <https://doi.org/10.1016/j.bioeco.2024.100072>
- Schlecht V, Vargas-Carpintero R, von Cossel M, Lewandowski I (2025) Developing marginal-land-based bioeconomy systems—a design and development approach for bio-based value chains and webs. *GCB Bioenergy* 17(5). <https://doi.org/10.1111/gcbb.v17.5>, <https://doi.org/10.1111/gcbb.70034>
- Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, Biggs R, Carpenter SR, de Vries W, de Wit CA, Folke C, Gerten D, Heinke J, Mace GM, Persson LM, Ramanathan V, Rayers B, Sörlin S (2015) Planetary boundaries: guiding human development on a changing planet. *Science* 347. <https://doi.org/10.1126/SCIENCE.1259855>
- Stegmann P, Londo M, Junginger M (2020) The circular bioeconomy: its elements and role in European bioeconomy clusters. *Resour Conserv Recycl* X 6:100029. <https://doi.org/10.1016/j.rcrx.2019.100029>
- Trenkner M, Kiesel A, Bauerle A, Chaumette C, Schlecht V, Kurz J, Zeitner P, Lewandowski I (2025) Closing the nutrient loop between urban and rural areas: a case study analyzing the technical potential of recycling fertilizers from urban biorefineries. *Biofuels Bioprod Biorefin* 19(6):2025–2046. <https://doi.org/10.1002/bbb.v19.6>, <https://doi.org/10.1002/bbb.2801>
- Ubando AT, Felix CB, Chen W-H (2020) Biorefineries in circular bioeconomy: a comprehensive review. *Bioresour Technol* 299:122585. <https://doi.org/10.1016/j.biortech.2019.122585>
- United Nations Brundtland Commission (1987) Report of the World Commission on Environment and Development: 'Our common future'. Available at: <https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf>,
- Vargas-Carpintero R (2025) Development of an integrated multi-criteria framework to assess the implementation potential of biobased value chains and webs with a territorial approach. *Ind Crop Prod* 223:120104. <https://doi.org/10.1016/j.indcrop.2024.120104>
- Vargas-Hernandez JG, Pallagst K, Hammer P (2018) Bio-economy at the crossroads of sustainable development. *Revista Internacional Interdisciplinar INTERthesis* 15(3):20–37. <https://doi.org/10.5007/1807-1384.2018v15n3p20>
- Wellisch M, Jungmeier G, Karbowski A, Patel MK, Rogulska M (2010) Biorefinery systems—potential contributors to sustainable innovation. *Biofuels Bioprod Biorefin* Wiley 4(3):275–286

- Wohlfahrt J, Ferchaud F, Gabrielle B, Godard C, Kurek B, Loyce C, Therond O (2019) Characteristics of bioeconomy systems and sustainability issues at the territorial scale. A review. *J Clean Prod* 232:898–909. <https://doi.org/10.1016/j.jclepro.2019.05.385>
- Zeug W, Bezama A, Moesenfechtel U, Jähkel A, Thrän D (2019) Stakeholders' interests and perceptions of bioeconomy monitoring using a sustainable development goal framework. *Sustainability* 11(6):1511
- Zeug W, Bezama A and Thrän D (2020) Towards a holistic and integrated Life Cycle Sustainability Assessment of the bioeconomy: Background on concepts, visions and measurements (UFZ Discussion Paper 7/2020). Helmholtz-Zentrum für Umweltforschung (UFZ). Available at: <https://hdl.handle.net/10419/224078>
- Zeug W, Bezama A, Thrän D (2021) A framework for implementing holistic and integrated life cycle sustainability assessment of regional bioeconomy. *Int J Life Cycle Assess* 26(10):1998–2023. <https://doi.org/10.1007/s11367-021-01983-1>
- Zukunftsagentur Rheinisches Revier (2021) Wirtschafts- und Strukturprogramm für das Rheinische Zukunftsrevier 1.1. Available at: https://www.rheinisches-revier.de/media/wsp_1.1.pdf

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.



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>)

Contents

- 4.1 The Bio-Based Value Chain as an Integrative Framework: An Introduction – 75**
 - 4.1.1 Relevance and Utility of the Concept – 75
 - 4.1.2 Concept of Bio-Based Value Chain – 76
- 4.2 The Origins of the Bio-Based Value Chain Concept – 78**
- 4.3 The Bio-Based Value Web: Beyond Linear Thinking – 79**

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/978-3-032-09098-0_4. 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.

4.4	Characteristics of Bio-Based Value Chains and Webs – 80
4.4.1	Biomass Dependency – 81
4.4.2	Biomass Complexity – 81
4.4.3	Multiple Biomass Uses – 82
4.4.4	Integrated Processing and Multi-product System – 83
4.4.5	Multi-sectoriality and Involvement of Multiple Stakeholders – 83
4.4.6	Territoriality or Regionality – 84
4.4.7	Context Dependency and Multi-dimensionality – 85
4.4.8	Sustainability Orientation – 86
4.4.9	Knowledge Base and Systemic Innovations – 86
4.5	Design and Development of Bio-Based Value Chains and Webs – 87
4.5.1	Design and Development Approaches – 89
4.5.2	Integrating Design and Development Tools with a Territorial Approach – 90
	References – 93

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.

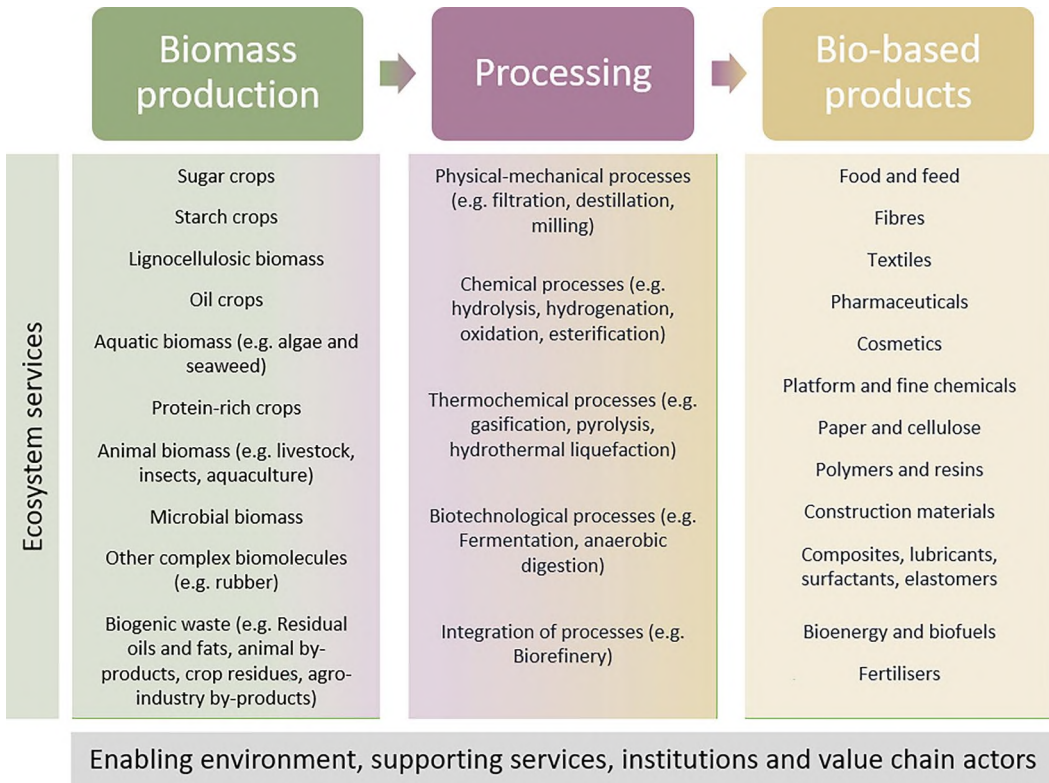
4.1.2 Concept of Bio-Based Value Chain

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.



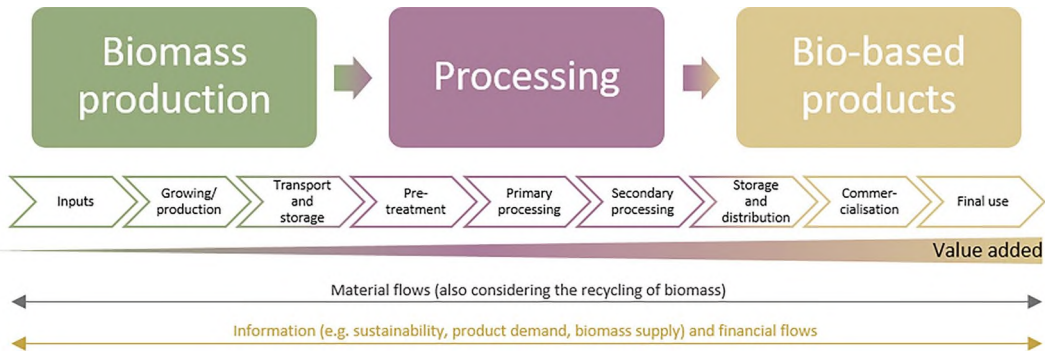
■ Fig. 4.1 Simplified structure of a bio-based value chain with its main components (Adapted from Iffland et al. 2015 and Abdulsamad et al. 2013)

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 indirect 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 multi-dimensional 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 Feeny 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 and 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).

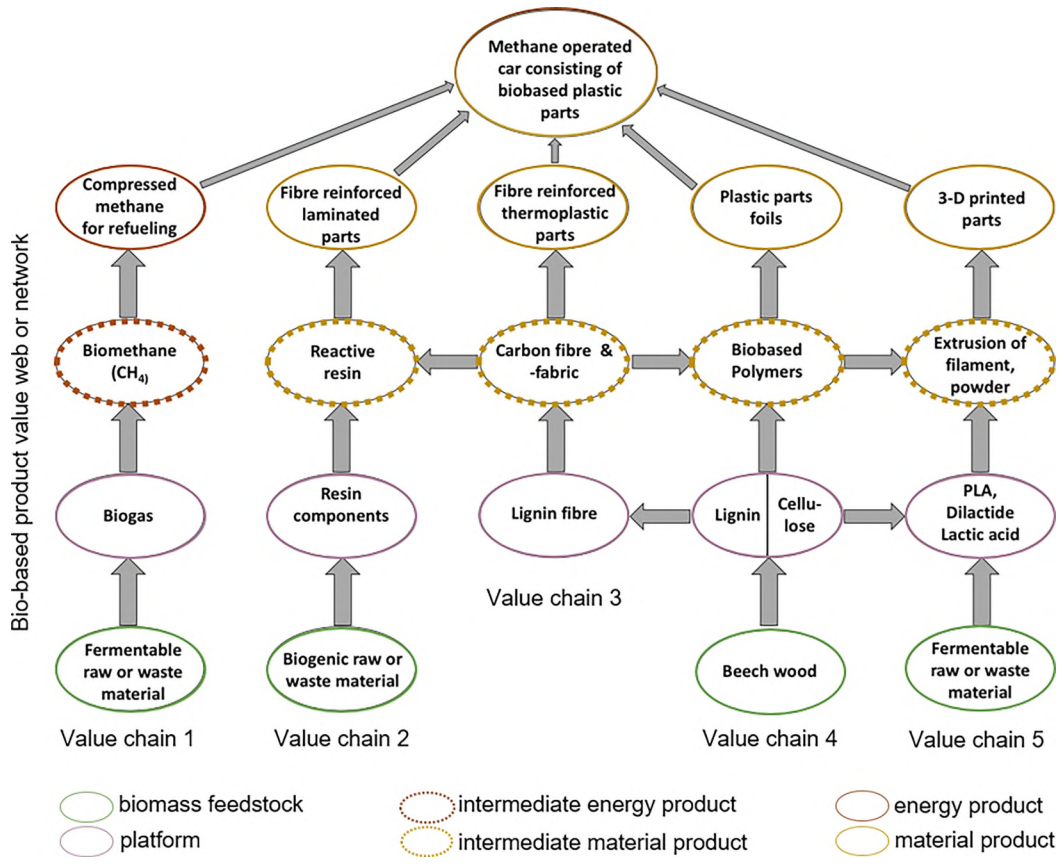


Fig. 4.3 Value web or network of a car operated with bio-methane and built with bio-based plastic parts. Multiple value chains are integrated, consisting of feedstock (biomass), platforms or building blocks, intermediate products and final material and energetic products. (Adapted from BIOPRO in Zörb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

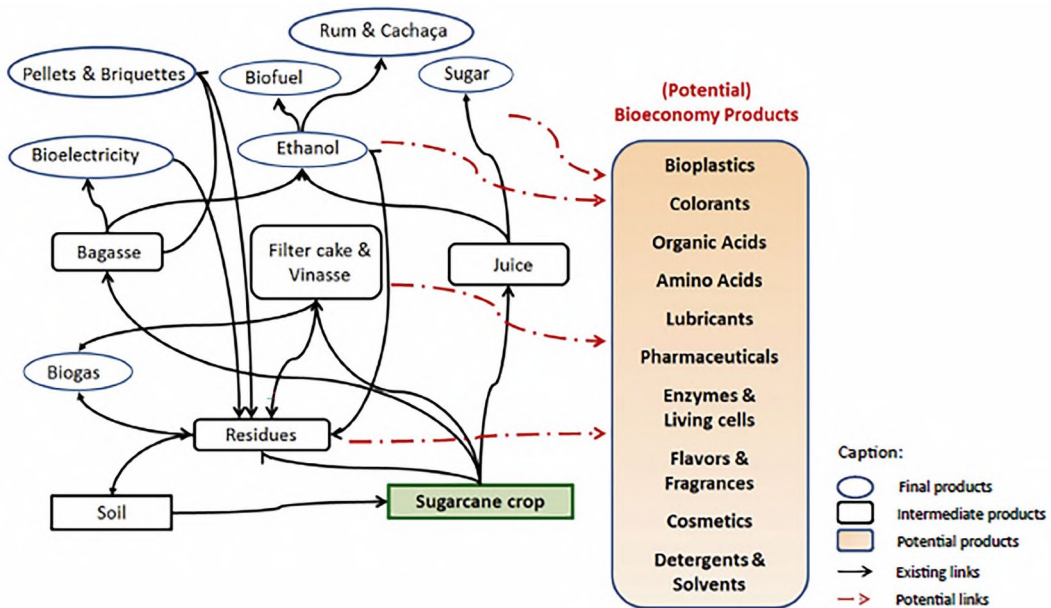
A *biomass-based value web* represents an extension of the value chain concept used to analyse the manifold uses of biomass in the bioeconomy. A biomass-based value web approach utilises the ‘web perspective’ as a multi-dimensional framework to understand the interrelation and linkages between several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

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.

Do you want to learn more about the concepts of bio-based value chains and webs? Take a look at [Supplementary Video](#)



■ 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 (Carrarsi 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).

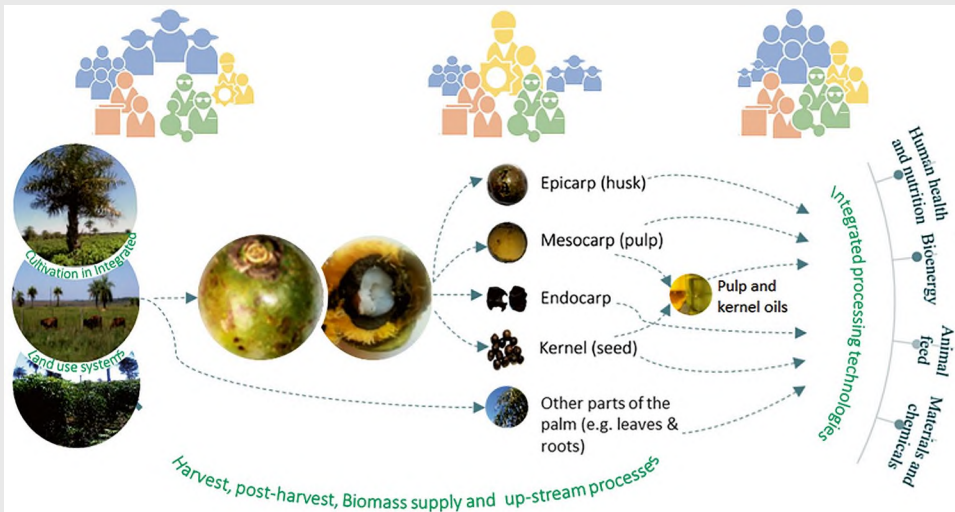


Fig. 4.5 *Acrocomia* value web concept depicting integrated land use systems for the cultivation the macaúba palm (*Acrocomia aculeata*) and other palms of the genus *Acrocomia*, the integral use of fruits as main plant product and the range of bioeconomy sectors for macaúba-based products and oils, 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.

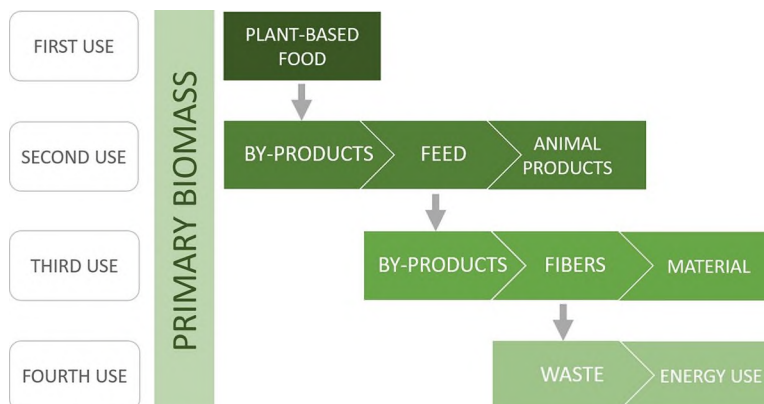
4.4.4 Integrated Processing and Multi-product System

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 cascad-

ing 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).

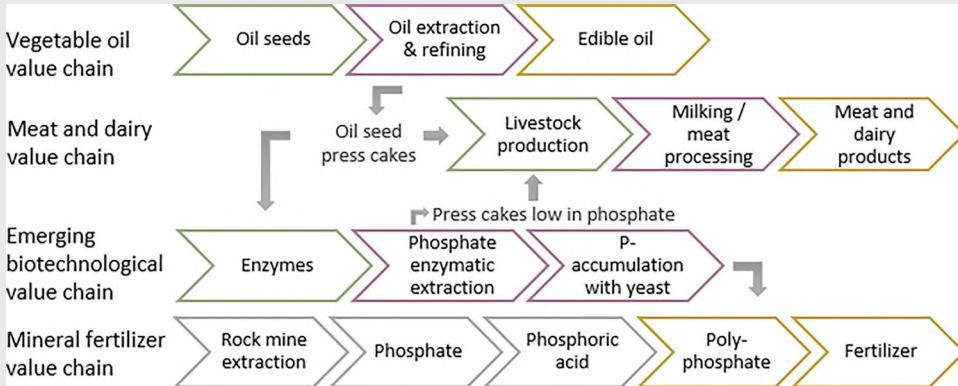


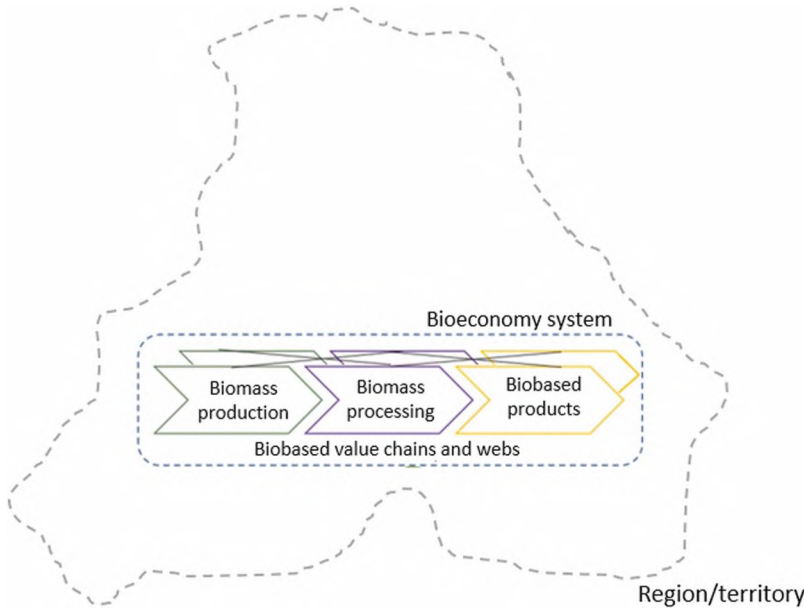
Fig. 4.7 Multi-sectoriality in emerging bio-based value chains and webs. An example is the phosphorus recovery from agricultural by-products such as oil press cakes from rapeseed to produce fertilizer and the use of press cake low in phosphate as animal feeding. (Adapted from Carraresi et al. 2018)

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

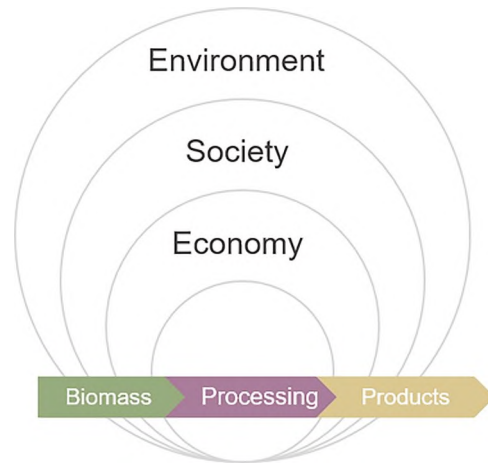
chain processes at regional level (Viaggi 2018; Kircher 2021). The approach of using available bio-based resources, adding value locally, operating in close proximity to the market, and contributing to rural economies, in addition to the geographical distribution of biomass, highlights the regional or 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 sys-



■ **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)

tems (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-

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 bio-economy 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-Oliveira 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-

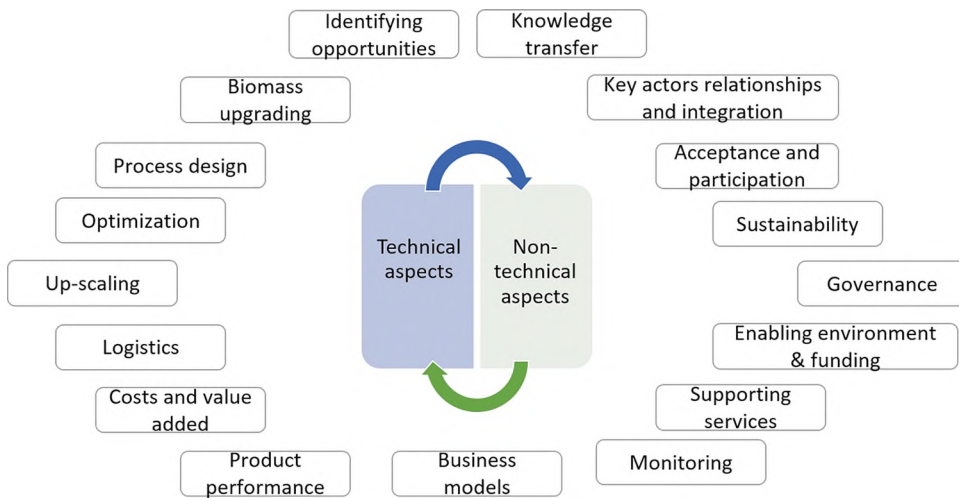


Fig. 4.11 Technical and non-technical aspects that are considered in the design and development of bio-based value chains and webs

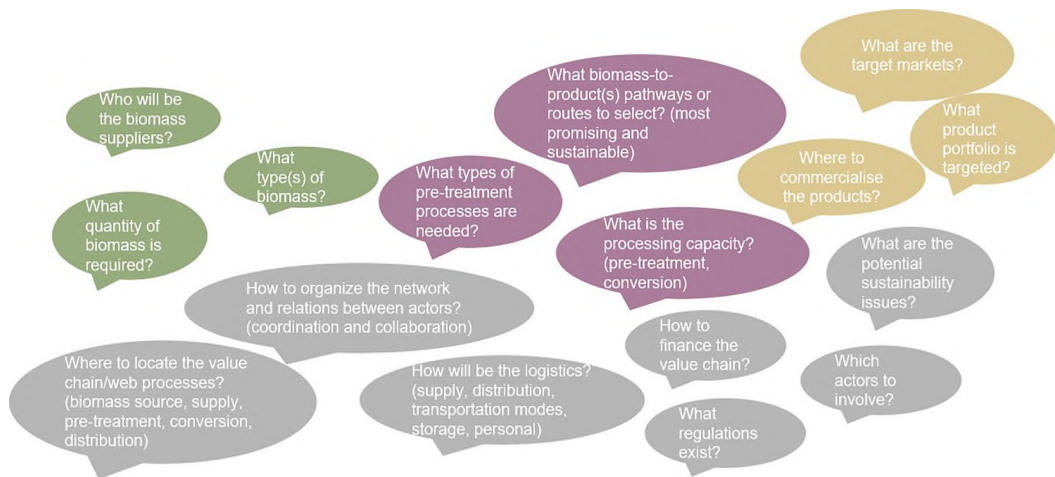


Fig. 4.12 Common strategic questions faced by decision-makers in the design and development of bio-based value chains and webs

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 config-

uration 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).

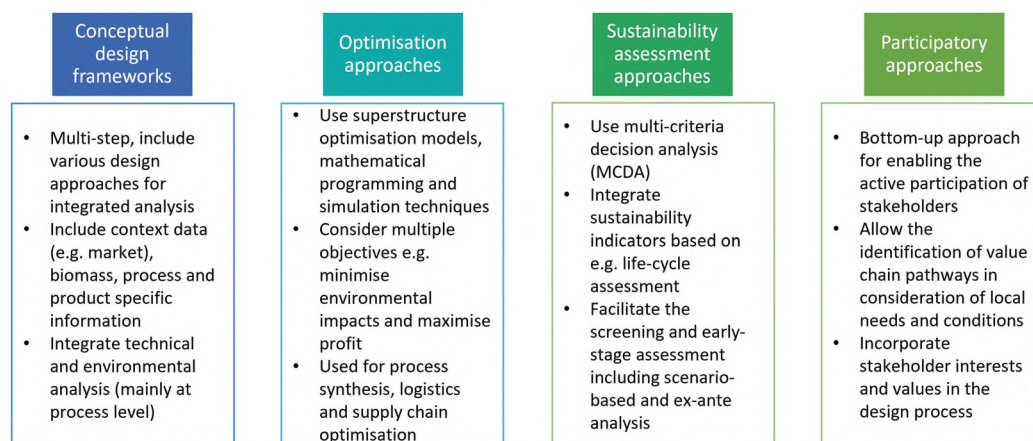


Fig. 4.13 Existing design frameworks and methods in the context of bio-based value chains and webs. (Adapted from Based on Espinoza Pérez et al. 2017; Palmeros Parada et al. 2017, 2020; Aristizábal-Marulanda and Cardona 2019; Benali et al. 2018; Vargas-Carpintero 2025)

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.

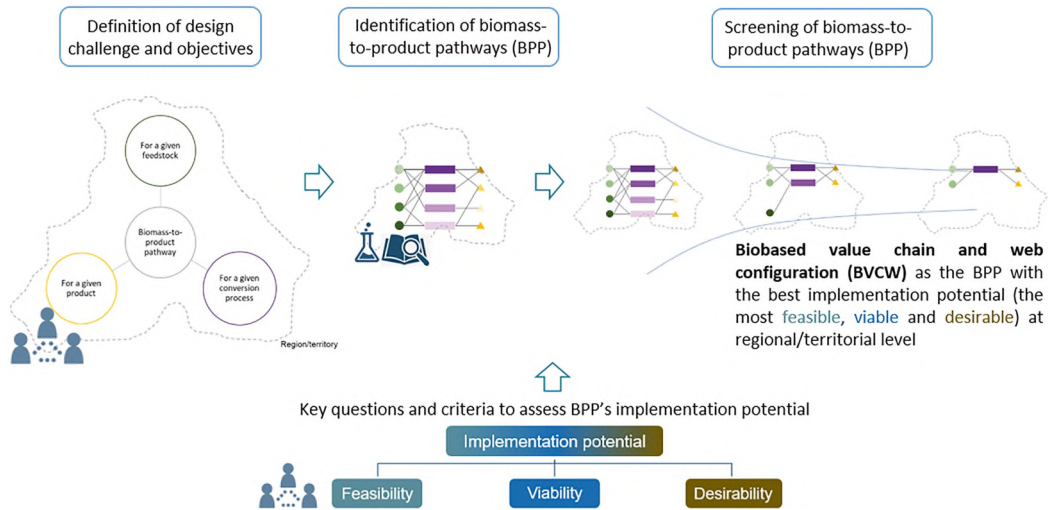
Considering the need of contextualizing the design and development process and advancing the integration of social aspects in the design process, bottom-up approaches are being increasingly developed and applied. This is the case of participatory design approaches,

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 bio-refinery 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

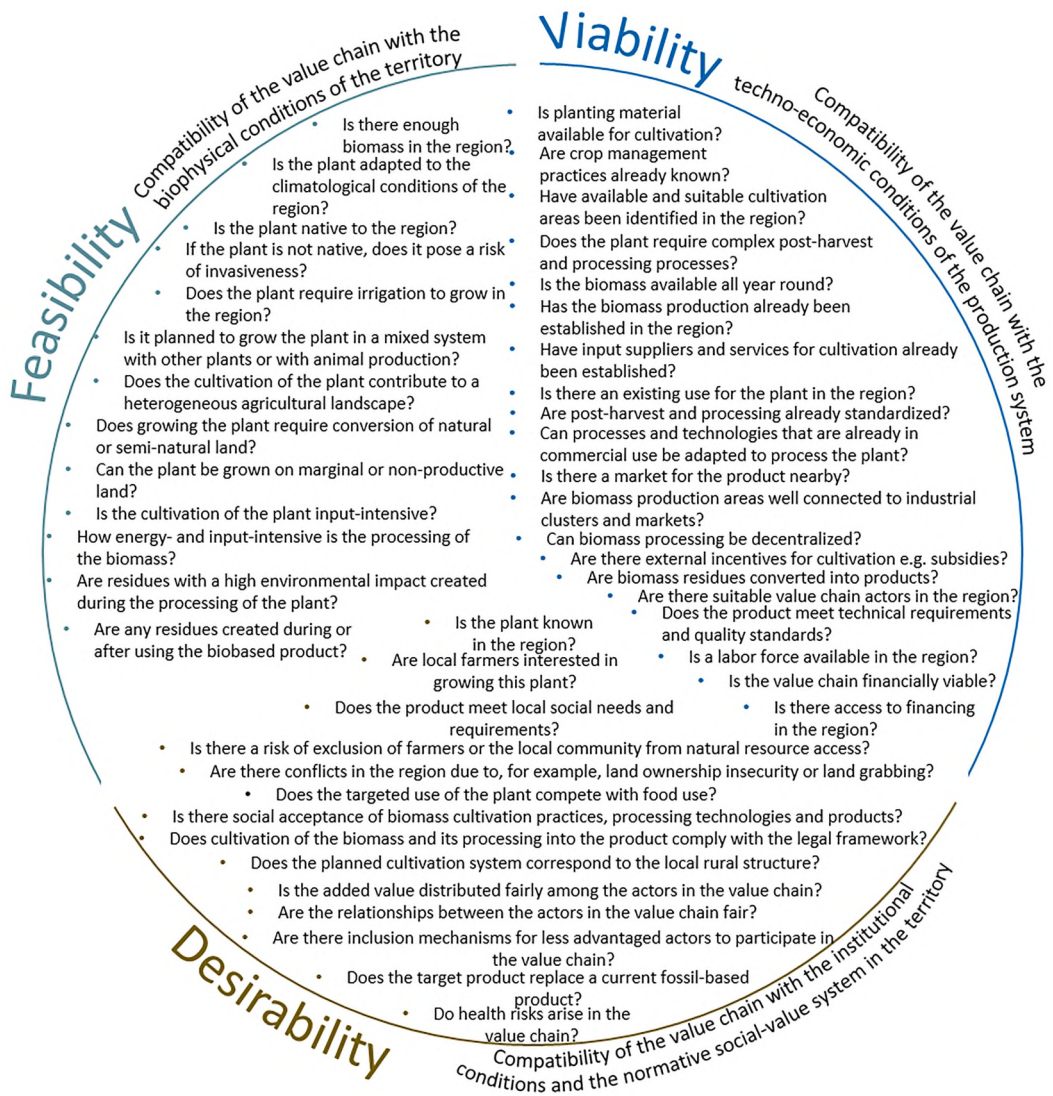


Fig. 4.15 Exemplary check questions to assess the implementation potential of bio-based value chains and webs from plant-based biomass. (Based on Vargas-Carpintero 2025)

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?

References

- Abdul Razik AH, Khor CS, Elkamel A (2019) A model-based approach for biomass-to-bioproducts supply Chain network planning optimization. *Food Bioprod Process* 118:293–305. <https://doi.org/10.1016/j.fbp.2019.10.001>
- Abdulsamad A, Brun L, Gereffi G (2013) Realizing the potential of African agriculture: innovations and market access for smallholder farmers. Duke University, Center on Globalization, Governance & Competitiveness. <https://doi.org/10.2139/ssrn.2598875>
- Aristizábal-Marulanda V, Cardona Alzate CA (2019) Methods for designing and assessing biorefineries: review. *Biofuels Bioprod Biorefining* 13:789–808
- Balaman ŞY, Wright DG, Scott J, Matopoulos A (2018) Network design and technology management for waste to energy production: an integrated optimization framework under the principles of circular economy. *Energy* 143:911–933. <https://doi.org/10.1016/j.energy.2017.11.058>
- Bastos Lima MG (2018) Toward multipurpose agriculture: food fuels flex crops and prospects for a bioeconomy. *Glob Environ Politics* 18(2):143–150. https://doi.org/10.1162/glep_a_00452
- Bastos Lima MG, Palme U (2022) The Bioeconomy–biodiversity nexus: enhancing or undermining nature's contributions to people? *Conservation* 2(1):7–25. <https://doi.org/10.3390/conservation2010002>
- Benali M, Jaaidi J, Mansoornejad B et al (2018) Decision support systems for assessment of biorefinery transformation strategies. *Can J Chem Eng* 96:2155–2175. <https://doi.org/10.1002/cjce.23301>
- Bezama A, Ingrao C, O'Keeffe S, Thrän D (2019) Resources, collaborators, and neighbors: the three-pronged challenge in the implementation of bioeconomy regions. *Sustainability* 11:7235. <https://doi.org/10.3390/su11247235>
- Biénabe E, Caron P, Loeillet D, Rival A (2017) Introduction. In: *Sustainable development and tropical agri-chains*. Springer, Dordrecht, pp 1–13
- Birner R (2018) Bioeconomy concepts. In: Lewandowski I, Gaudet N, Lask J, Maier J, Tchouga B, Vargas-Carpintero R (eds) *Bioeconomy, shaping the transition to a sustainable, biobased economy*. Springer International Publishing, Cham, pp 17–38

- Bocken NMP, Harsch A, Weissbrod I (2022) Circular business models for the fastmoving consumer goods industry: desirability, feasibility, and viability. *Sustain Prod Consum* 30:799–814. <https://doi.org/10.1016/j.spc.2022.01.012>
- Bröring S, Laibach N, Wustmans M (2020) Innovation types in the bioeconomy. *J Clean Prod* 266:121939. <https://doi.org/10.1016/j.jclepro.2020.121939>
- Budzianowski WM, Postawa K (2016) Total chain integration of sustainable biorefinery systems. *App Energy* 184:1432–181446. <https://doi.org/10.1016/j.apenergy.2016.06.050>
- Bugge M, Hansen T, Klitkou A (2016) What is the bioeconomy? A review of the literature. *Sustainability* 8:691. <https://doi.org/10.3390/su8070691>
- Butemann H, Schimmelpfeng K (2017) Structuring the planning tasks in biomass-based supply chains. In: Dabbert S, Lewandowski I, Weiss J, Pyka A (eds) *Knowledge-driven developments in the bioeconomy* (pp 293–311). Springer. https://doi.org/10.1007/978-3-319-58374-7_15
- Cardona Alzate CA, Ortiz-Sanchez M, Solarte-Toro JC (2023) Design strategy of food residues biorefineries based on multifeedstocks analysis for increasing sustainability of value chains. *Biochem Eng J* 194:108857. <https://doi.org/10.1016/j.bej.2023.108857>
- Cardona C, Moncada J, Aristizábal-Marulanda V (2019) *Biorefineries: design and analysis*. CRC Press, Boca Raton
- Carraresi L, Berg S, Bröring S (2018) Emerging value chains within the bioeconomy: structural changes in the case of phosphate recovery. *J Clean Prod* 183:87–101. <https://doi.org/10.1016/j.jclepro.2018.02.135>
- Cerca M, Sosa A, Gusciute E, Murphy F (2022) Strategic planning of bio-based supply chains: unlocking bottlenecks and incorporating social sustainability into biorefinery systems. *Sustain Prod and Consum* 34:219–34232. <https://doi.org/10.1016/j.spc.2022.09.013>
- Diaz-Chavez R, van Dam J (2020) Novel regional governance approaches and landscape-based approaches to govern sustainability of bioenergy and biomaterials supply chains. International Energy Agency (IEA) Bioenergy. Task 43: TR2020-02. <https://www.ieabioenergy.com/wp-content/uploads/2020/07/Novel-regional-and-landscape-based-approaches-to-govern-sustainability-of-bioenergy-and-biomaterials-supply-chains.pdf>
- Espinoza Pérez AT, Camargo M, Narváez Rincón PC, Alfaro Marchant M (2017) Key challenges and requirements for sustainable and industrialized biorefinery supply chain design and management: a bibliographic analysis. *Renew Sust Energ Rev* 69:350–359. <https://doi.org/10.1016/j.rser.2016.11.084>
- Ge L, Anten NP, van Dixhoorn IDE et al (2016) Why we need resilience thinking to meet societal challenges in bio-based production systems. *Curr Opin Environ Sustain* 23:17–27. <https://doi.org/10.1016/j.cosust.2016.11.009>
- Gereffi G, Humphrey J, Sturgeon T (2005) The governance of global value chains. *Rev Int Polit Econ* 12(1):78–104
- Giampietro M (2023) Multi-scale integrated analysis of societal and ecosystem metabolism. In: Villamayor-Tomas S, Muradian R (eds) *The Barcelona School of Ecological Economics and Political Ecology. Studies in ecological economics*, vol 8. Springer Cham, pp 109–121
- Iffland K, Sherwood J, Carus M, Raschka A, Farmer T, Clark J (2015) Definition, calculation and comparison of the “Biomass Utilization Efficiencies (BUE)” of various bio-based chemicals, polymers and fuels. Nova-institute. <http://www.bio-based.eu/nova-papers>
- Kaplinsky R, Morris M (2002) *A handbook for value chain research*. International Development Research Centre (IDRC). https://www.fao.org/fileadmin/user_upload/fisheries/docs/Value_Chain_Handbook.pdf
- Kircher M (2021) Bioeconomy—present status and future needs of industrial value chains. *New Biotechnol* 60:96–104. <https://doi.org/10.1016/j.nbt.2020.09.005>
- Lago-Oliveira S, Arias A, Rebolledo-Leiva R, Feijoo G, González-García S, Moreira MT (2024) Monitoring the bioeconomy: value chains under the framework of life cycle assessment indicators. *Clean Circ Bioeconomy* 7100072. <https://doi.org/10.1016/j.clcb.2024.100072>
- Lançon F, Temple L, Biénabe E (2017) The concept of Filière or value chain: an analytical framework for development policies and strategies. In: *Sustainable development and tropical agri-chains*. Springer, Dordrecht, pp 17–28
- Lewandowski I (2015) Securing a sustainable biomass supply in a growing bioeconomy. *Glob Food Sec* 6:34–42. <https://doi.org/10.1016/j.gfs.2015.10.001>
- Lewandowski I (2017) Increasing biomass production to sustain the bioeconomy. In: Dabbert S, Lewandowski I, Weiss J, Pyka A. (eds) *Knowledge-driven developments in the bioeconomy. Economic Complexity and Evolution*. Springer, Cham. https://doi.org/10.1007/978-3-319-58374-7_10
- Lewandowski I, von Cossel M, Winkler B, Bauerle A, Gaudet N, Kiesel A, Lewin E, Magenau E, Marting Vidaurre NA, Müller B, Schlecht V, Thumm U, Trenkner M, Vargas-Carpintero R, Weickert S, Weik J, Reinmuth E (2024) An adapted indicator framework for evaluating the potential contribution of bioeconomy approaches to agricultural systems resilience. *Adv Sustain Sys* 8(7) <https://doi.org/10.1002/adsu.v8.7>, <https://doi.org/10.1002/adsu.202300518>
- Lokesh K, Ladu L, Summerton L (2018) Bridging the gaps for a ‘Circular’ bioeconomy: selection criteria,

- bio-based value chain and stakeholder mapping. *Sustainability* 10:1695. <https://doi.org/10.3390/su10061695>
- Lucian Ceapraz I, Kotbi G, Sauvée L (2016) The territorial biorefinery as a new business model. *Bio-based Appl Econ*. <https://doi.org/10.13128/BAE-15379>
- Mac Clay P, Sellare J (2022) Value chain transformations in the transition to a sustainable bioeconomy. *SSRN Electron J*. <https://doi.org/10.2139/ssrn.4193583>
- Mac CP, Feeney R (2019) Analyzing agribusiness value chains: a literature review. *Int Food Agribus Manag Rev* 22:31–46. <https://doi.org/10.22434/IFAMR2018.0089>
- Marting Vidaurre NA, Vargas-Carpintero R, Wagner M, Lask J, Lewandowski I (2020) Social aspects in the assessment of biobased value chains. *Sustainability* 12(23):9843. <https://doi.org/10.3390/su12239843>
- Mertens A, Van Lancker J, Buysse J et al (2019) Overcoming non-technical challenges in bioeconomy value-chain development: learning from practice. *J Clean Prod* 231:10–20. <https://doi.org/10.1016/j.jclepro.2019.05.147>
- Moncada J, Aristizábal V, Cardona C (2016) Design strategies for sustainable biorefineries. *Biochem Eng J* 116:122–134. <https://doi.org/10.1016/j.bej.2016.06.009>
- Nang'ole E, Mithöfer D, Franzel S (2011) Review of guidelines and manuals for value chain analysis for agricultural and forest products. Occasional Paper 17. World Agroforestry Centre, Nairobi
- Palmeros Parada M, Osseweijer P, Posada Duque JA (2017) Sustainable biorefineries, an analysis of practices for incorporating sustainability in biorefinery design. *Ind Crop Prod* 106:105–123. <https://doi.org/10.1016/j.indcrop.2016.08.052>
- Palmeros Parada M, Asveld L, Osseweijer P, Posada JA (2020) Integrating value considerations in the decision making for the design of biorefineries. *Sci Eng Ethics* 26:2927–2955. <https://doi.org/10.1007/s11948-020-00251-z>
- Patel AD, Meesters K, den Uil H et al (2012) Sustainability assessment of novel chemical processes at early stage: application to biobased processes. *Energy Environ Sci* 5:8430. <https://doi.org/10.1039/c2ee21581k>
- Patel AD, Meesters K, den Uil H et al (2013) Early-stage comparative sustainability assessment of new biobased processes. *ChemSusChem* 6:1724–1736. <https://doi.org/10.1002/cssc.201300168>
- Porter ME (1985) *Competitive advantage. Creating and sustaining superior performance*. The Free Press, New York
- Posada JA, Patel AD, Roes A et al (2013) Potential of bioethanol as a chemical building block for biorefineries: preliminary sustainability assessment of 12 bioethanol-based products. *Bioresour Technol* 135:490–499. <https://doi.org/10.1016/j.biortech.2012.09.058>
- Pyka A (2017) Transformation of economic systems: the bio-economy case. In: Dabbert S, Lewandowski I, Weiss J, Pyka A. (eds) *Knowledge-driven developments in the bioeconomy. Economic Complexity and Evolution*. Springer, Cham. https://doi.org/10.1007/978-3-319-58374-7_1
- Ronzon T, Tamosiunas S, Mbarek R (2022) *Jobs and growth in the bioeconomy*. Publications Office of the European Union, Luxembourg, ISBN 978-92-76-47130-1. <https://doi.org/10.2760/323093>. JRC128361
- Scheiterle L, Ulmer A, Birner R, Pyka A (2018) From commodity-based value chains to biomass-based value webs: the case of sugarcane in Brazil's bioeconomy. *J Clean Prod* 172:3851–3863. <https://doi.org/10.1016/j.jclepro.2017.05.150>
- Schlecht V, Vargas-Carpintero R, von Cossel M, Lewandowski I (2025) Developing marginal-land-based bioeconomy systems a design and development approach for bio-based value chains and webs. *GCB Bioenergy* 17(5):e70034. <https://doi.org/10.1111/gcbb.70034>
- Sharifzadeh M, Garcia MC, Shah N (2015) Supply chain network design and operation: systematic decision-making for centralized, distributed, and mobile biofuel production using mixed integer linear programming (MILP) under uncertainty. *Biomass Bioenergy* 81:401–414. <https://doi.org/10.1016/j.biombioe.2015.07.026>
- Van Lancker J, Wauters E, Van Huylenbroeck G (2016) Managing innovation in the bioeconomy: an open innovation perspective. *Biomass and Bioenergy* 9060–9069. <https://doi.org/10.1016/j.biombioe.2016.03.017>
- Vargas-Carpintero R (2025) Development of an integrated multi-criteria framework to assess the implementation potential of biobased value chains and webs with a territorial approach. *Ind Crop Prod* 223:120104. <https://doi.org/10.1016/j.indcrop.2024.120104>
- Vargas-Carpintero R, Hilger T, Mössinger J et al (2021) *Acrocomia* spp.: neglected crop, ballyhooed multi-purpose palm or fit for the bioeconomy? A review. *Agronomy for Sustainable Development*
- Vargas-Carpintero R, Hilger T, Tiede K et al (2022) A collaborative, systems approach for the development of biomass-based value webs: the case of the *Acrocomia* Palm. *Land* 11:1748. <https://doi.org/10.3390/land11101748>
- Viaggi D (2018) *The bioeconomy: delivering sustainable green growth*, 1st edn. CABI. e-ISBN: 9781786392763
- Virchow D, Beuchelt TD, Kuhn A, Denich M (2016) Biomass-based value webs: a novel perspective for emerging bioeconomies in sub-Saharan Africa. In: Gatzweiler F, von Braun J (eds) *Technological and*

institutional innovations for marginalized smallholders in agricultural development. Springer, Cham. https://doi.org/10.1007/978-3-319-25718-1_14

Virchow D, Beuchelt TD, Kuhn A, Denich M (2016) Biomass-based value webs: a novel perspective for emerging bioeconomies in sub-Saharan Africa. In: Gatzweiler F, von Braun J (eds) Technological and institutional innovations for marginalized smallholders in agricultural development. Springer International Publishing, pp 225–238

Wohlfahrt J, Ferchaud F, Gabrielle B, Godard C, Kurek B, Loyce C, Therond O (2019) Characteristics of bioeconomy systems and sustainability issues at the territorial scale. A review. *J Clean Prod* 232898–232909. <https://doi.org/10.1016/j.jclepro.2019.05.385>

Zörb C, Lewandowski I, Kindervater R, Götttert U, Patzelt D (2018) Biobased resources and value chains. In: Lewandowski I, Gaudet N, Lask J, Maier J, Tchouga B, Vargas-Carpintero R (eds) *Bioeconomy*. Springer, Cham. https://doi.org/10.1007/978-3-319-68152-8_5

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

