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Natural Resource Management and Policy
Series Editors: David Zilberman · Renan Goetz · Alberto Garrido

David Zilberman
Jie Zhuang
Justus Wesseler
Madhu Khanna *Editors*

Handbook of Circular Bioeconomy

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Series Editors

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There is a growing awareness to the role that natural resources, such as water, land, forests and environmental amenities, play in our lives. There are many competing uses for natural resources, and society is challenged to manage them for improving social well-being. Furthermore, there may be dire consequences to natural resources mismanagement. Renewable resources, such as water, land and the environment are linked, and decisions made with regard to one may affect the others. Policy and management of natural resources now require interdisciplinary approaches including natural and social sciences to correctly address our society preferences.This series provides a collection of works containing most recent findings on economics, management and policy of renewable biological resources, such as water, land, crop protection, sustainable agriculture, technology, and environmental health. It incorporates modern thinking and techniques of economics and management. Books in this series will incorporate knowledge and models of natural phenomena with economics and managerial decision frameworks to assess alternative options for managing natural resources and environment.

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Handbook of Circular Bioeconomy

Springer

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Preface

Interdisciplinary collaboration is crucial for the catalyzation and development of sustainable solutions to the challenges we face today in food, energy, natural resources, and economy. Since the world is connected through complex, interactive supply and value chains, international learning and communications are key to the outcomes of economic partnerships, technology innovations, and opportunity exploration. Such actions are especially important today when economic and geopolitical landscapes are being reshaped.

This book integrates concepts, knowledge, experiences, practices, and policies of the circular bioeconomy through 120 authors who represent 17 countries. It is one of the significant outcomes of the international symposium on *Food-Energy-Water Bioeconomies for Net-Zero Transition*. The event was held from March 18 to 20, 2024, in Knoxville, Tennessee, USA, with the sponsorship of the research projects of the US National Science Foundation (NSF).

The publishing of this book indicates the success of teamwork across disciplines and countries. The coordination processes of invitation, submission, peer-review, revision, and finalization of the 28 chapters were very dynamic and challenging. However, the processes brought many intrinsic rewards beyond intellectual advancement, such as trust establishment, team consolidation, opportunity identification, and new visions. Writing and publishing are far more process journeys than a destination—book completion. We expect new journeys to extend the work of this book toward more substantial international collaborations across disciplines, sectors, cultural backgrounds, and socioeconomic systems.

The publishing of this book involved many people behind the scenes. They provided vision, opportunity, encouragement, and critique. Among them, Ms. Sara Mulville played a key role in connecting and communicating with such many editors and contributing authors. We wish to thank all editors and authors for their work and time, NSF, and the University of Tennessee for supporting the 2024 symposium,

and the University of California, Berkeley, for supporting open access to this book. Writing a book with many scholars is a very effective approach to building interdisciplinary teams for research collaboration.

Berkeley, CA — David Zilberman
Knoxville, TN — Jie Zhuang
Wageningen, The Netherlands — Justus Wesseler
Urbana, IL — Madhu Khanna

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About the Editors

David Zilberman is a Distinguished Professor of Agricultural and Resource Economics at UC Berkeley. He received the 2019 Wolf Prize in Agriculture and was elected a member of the US National Academy of Sciences in 2019. A description of David's work and career appears here. David served as the 2018–19 President of the Agricultural & Applied Economics Association (AAEA). He's a fellow of multiple professional associations and has published in professional and popular outlets. He has over 400 refereed journal articles ranging from Science to ARE-Update and has edited 30 books. In addition, he has served as a Consultant to the US Environmental Protection Agency, USDA, the World Bank, FAO, MARS, BP, WWF, Shell, and others. David earned a BA from Tel Aviv University and a Berkeley Ph.D. David co-founded the Beahrs Environmental Leadership Program, the International Consortium of Applied Bioeconomy Research and is the founder and academic director of the Berkeley MDP program. David's research analyzes water, innovation, supply chain, agriculture, energy, and the environment. He has researched the economics and political economy of COVID-19 and of agricultural biotechnology, and the potential of the bioeconomy. During the last 2 years, he has studied the economics and supply chain design of Black Soldier Fly waste management systems.

Jie Zhuang is a professor in the Department of Biosystems Engineering and Soil Science, director of environmental and soil science graduate studies, and the lead of the university cluster hire initiative of resilient agriculture and forest systems at the University of Tennessee (UT) in Knoxville, Tennessee, USA. He is also an advisory council member of the UT Institute of Agriculture and an affiliated faculty of the UT Institute for a Secure and Sustainable Environment and the Institute of Energy and Environment. He has served on numerous award committees of scientific organizations and proposal review panels of national and international funding agencies. Dr. Zhuang's research topics range from the fate and transport of contaminants (such as viruses, bacteria, organic chemicals, metals, engineering colloids, and nutrients) to soil hydrological modeling, crop–water relations, carbon–water–nutrient interactions, food–energy–water nexus, and circular food systems. He links environmental soil science to food–energy–water nexus by innovating solutions for soil restoration and resilience, safe reclaimed water irrigation, and regenerative agriculture. He has published ~170 refereed articles and book chapters and ~100 conference abstracts. His current research projects aim to develop climate-smart food-energy-water nexus on smallholder farms.

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Part I
Strategies and Impacts of a Circular Bioeconomy

Chapter 1
What Is the Bioeconomy and How Does It Make a Difference? An Introduction

David Zilberman, Jie Zhuang, Justus Wesseler, and Madhu Khanna

1.1 Different Perspectives of the Bioeconomy

In Chap. 2, Verma and Jones present a perspective of scientists and engineers. Natural biochemical processes generated a wide array of bioresources—some served as essential sources of food, others were accumulated and stored energy. As human knowledge advanced, technologies were developed to harness and utilize fossilized resources efficiently. These new capabilities have significantly contributed to human growth and well-being.

However, they have also generated considerable environmental damage. The exploitation of bioresources has led to the contamination of land and water and release of greenhouse gases. The challenge ahead is to transition from a linear bioeconomy toward a circular bioeconomy that will usher sustainable development.

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Circularity implies reduction, reuse, and recycling of residue materials. It requires developing circular technologies, supply chains that develop them and utilize them and policies that provide the incentive and resources for a transition to a circular bioeconomy. This transformation demands multidisciplinary collaboration, with meaningful engagement between scientists, engineers, policymakers, and academia to develop effective mechanisms that enhance our collective capacity to address the climate crisis and build a more sustainable future.

In Chap. 3, Fox presents the bioeconomy perspective of the previous U.S. administration. Building the bioeconomy requires scaling up technologies and building circular bioeconomy value chains. After decades focused on biotech R&D, the USA shifted emphasis in 2022 with Executive Order 14081 ("Bioeconomy EO"), prioritizing investment in bio-based manufacturing at higher technology readiness levels. This shift encouraged broader stakeholder engagement, supported rural development, and advanced defossilization in energy and manufacturing. The EO aimed to leverage recent federal funding to reduce investment risk and attract greater private sector participation through public–private partnerships, promoting economies of scale and market competitiveness. While meaningful progress was made before the EO was rescinded, its impact could have been strengthened with more systematic investment prioritization across sectors and regions. Adopting such methodologies—based on global best practices—will be vital to meet the rigorous risk standards required for sustained private investment, especially amid tightening public budgets. A major challenge is developing methodologies to effectively enable allocation of public resources to provide support to establishment of new circular bioeconomy value chains.

Chapter 4 by Zilberman and collaborators explores how integrated supply chains can accelerate the shift to Circular Bioeconomy System (CBS). It emphasizes the role of government policies in shaping bioeconomy supply chains and recommends global investment in R&D and infrastructure to address climate change. Key policy tools include carbon pricing, targeted subsidies, and science-based regulation to ease the adoption of biotechnology—especially in developing countries. Overcoming resistance to biotechnology is essential for replacing fossil fuels with renewable alternatives. The chapter notes that considerations of profitability, risk, and scale can lead to market concentration among processors and retailers, prompting a need for policies that ensure competitiveness. The bioeconomy spans four sectors—green (land-based), blue (aquatic), brown (waste reuse), and white (biomanufacturing)—each with unique supply chain challenges. Achieving circularity requires converting production residues into inputs, supported by appropriate technologies, infrastructure, and regulation. These measures are vital to building resilient, efficient, and sustainable supply systems.

In Chap. 5, Wesseler and collaborators analyze EU bioeconomy investment using results from the BioMonitor project. The bioeconomy is seen as key to sustainable development, with circularity offering more efficient environmental outcomes. Investments have had varied results—some regions show strong success while others lag—largely due to differing policies and regulations. The chapter reports growth in value added and job creation, particularly in food, biofuels, and high-value chemicals. However, it argues that further growth requires greater use of modern biotechnologies. Modeling bioeconomy supply chains is complex due to the need to integrate multiple sectors, but the chapter demonstrates feasibility

through case studies. It concludes that while EU bioeconomy investments are starting to yield results, more is needed as this is still an early stage. A key challenge ahead is creating policies that harness new scientific knowledge and enable faster adoption of innovations to maximize societal benefit.

In Chap. 6, Matlock identifies some principles, implementation mechanisms, and policies to establishing a bioeconomy. The circular bioeconomy should prioritize renewable biological resources as primary inputs, should eliminate waste by keeping bio-based resources in use for as long as possible, advance regenerative design by turning biological waste and residues into valuable products. It should recognize biophysical and biological cycles and use life cycle assessment to monitor them and assess product performance. Policies to support the circular bioeconomy should eliminate regulatory and tax barriers for circularity, integrate agriculture, climate, energy, and the environment aiming to assure consistency, efficiency, and sustainability, and establish mechanisms for the enforcement of regulation and monitoring environmental conditions to detect random shocks.

In Chap. 7, Daniels and collaborators suggest that the circular bioeconomy should integrate circularity, which emphasizes reduction, reuse, and recycling of waste products, into regeneration, which emphasizes building resilience and enhancing capabilities. Regenerative agriculture emphasizes reduced waste, enhanced soil health and biodiversity, restoration of degraded ecosystems, and self-sustaining renewability. Regenerative systems emphasize adaptation to changing conditions and integration of new capabilities and knowledge. Introduction of regenerative systems requires continuous research and outreach, financial incentives to overcome barriers of adoption, and public and private collaborations to facilitate implementation of regenerative and circular systems.

In Chap. 8, Zilberman and collaborators examine how the emerging U.S. bioeconomy can contribute to historically underrepresented communities. It highlights opportunities in green (agriculture, forestry) and brown (waste reuse) sectors, such as specialty crops and composting. However, barriers like limited capital, institutional mistrust, and regulatory hurdles may limit participation by small-scale, minority, and female farmers. The chapter emphasizes the need for targeted education and workforce training, particularly through partnerships with land-grant universities and historically black colleges and universities. Realizing an inclusive bioeconomy will require coordinated policy, investment, and community engagement to ensure equitable access and sustainable growth.

In Chap. 9, Durmaz calls for comprehensive policy frameworks, refined economic tools, and cross-sector collaboration to realize the circular bioeconomy's (CB) potential. CB supports rural economic development, decentralization of production, and local empowerment. But its introduction is challenged by high investment costs, policy and regulatory uncertainties, technological immaturity, and land competition. Better measurement will enable overcoming these challenges. It is important to adapt metrics like the Levelized Cost of Production (LCOP) and Levelized Cost of Fuel (LCOF) to include co-product revenues, avoided emissions, and policy incentives. To overcome financial constraints for the bioeconomy, loan guarantees, blended finance, and regulatory stability are essential to lowering the weighted average cost of capital, particularly in emerging economies.

1.2 Addressing Specific Aspects of the Bioeconomy

Several chapters emphasize specific dimensions of the bioeconomy. In Chap. 10, Zhuang and collaborators suggest that specific measures are needed to enable smallholder farms to incorporate into the circular bioeconomy. However, these farms face limited access to resources, markets, financing, and technology. Smallholder considerations should be central to bioeconomy design, ensuring approaches are both affordable and practical. Collaborative participatory efforts among government agencies, researchers, engineers, and farmers, and targeted financial support, infrastructure investment, agricultural education, and policy reform are key to developing climate-smart, small-scale agriculture.

In Chap. 11, Guan and collaborators analyze bioeconomy strategies for decarbonization. Bioeconomy strategies complement renewables by leveraging biological systems to capture, substitute, and remove atmospheric CO_2. These strategies follow three pathways: photosynthesis, thermochemical conversion, and microbial processes. They involved either carbon sequestration, carbon substitution, or carbon removal approaches. Technology readiness varies. Afforestation, conventional biofuels, and bioplastics are commercially mature, while algae-based biofuels, microbial CO_2 conversion, and genetic engineering remain in earlier development stages. Economic feasibility also ranges widely, but some nature-based solutions like afforestation offer highly cost-effective mitigation ($4.2–16.9/ton CO_2).

In Chap. 12, Tomberlin and collaborators present a vision for harnessing an insect (black soldier fly) to solve waste problems and provide valuable products. Approximately 30–40% of food in the USA and EU is discarded annually. Excess manure from livestock degrades water and air quality and contributes to GHG emissions. Insects such as black soldier flies (BSF), crickets, and mealworms can convert food and organic waste into high-quality proteins, lipids, fertilizers, and biofuels. They grow rapidly, reproduce efficiently, thrive on diverse feedstocks, and require minimal land and water. Their capacity for vertical farming and circular bioconversion makes them attractive for sustainable food systems. Yet their commercialization is hampered by regulatory restrictions, public acceptance, and funding gaps.

In Chap. 13, Hochman and collaborators introduce the concept of the Climate--Smart Circular Bioeconomy (CSCB)—an integrated framework that combines climate-smart technologies with the principles of a circular bioeconomy. The CSCB highlights the potential of precision agriculture, agroforestry, cover crops, and soil health practices, when paired with modern biotechnology and digital tools, to enhance crop productivity, free up land for biofuel and agrivoltaic systems, and promote carbon sequestration. Green carbon storage and value creation can be further improved through reduced waste and the adoption of circular strategies. Successfully transitioning to a CSCB model requires coherent and coordinated agricultural, resource, and energy policies; global investment in research and education to build capacity; sound regulatory frameworks; and attention to equity and political economy considerations to ensure broad social and political acceptance.

In Chap. 14, Khanna and Fan examine various biofuel feedstock options—dedicated energy crops (miscanthus, switchgrass, energy cane), crop residues (corn stover), and forest or food wastes. These vary significantly in yield, production cost, and environmental impact across regions. While perennial energy crops offer high yields and substantial environmental benefits such as soil carbon sequestration and reduced nitrogen runoff, they also require high upfront investment and long-term land commitment. Crop residues are more readily available but may degrade soil health if overharvested. The authors find that volumetric mandates promote low--cost feedstocks, while carbon-based incentives more effectively support low-GHG pathways like perennial crops. They stress the need for stable, long-term policies, investment in bioconversion technologies, workforce development, and public education. Diversifying end markets (e.g., bioplastics) and improving logistics and technology integration will be key to overcoming barriers.

In Chap. 15, Seeger and collaborators explore the trajectory from biodiversity to microbial genomics and its application in biotechnology, underscoring how these advances contribute to a circular bioeconomy. Modern biotechnology employs cellular and molecular processes to develop bioeconomy solutions. Using advances in genomics and bioinformatics allows the prediction and engineering of metabolic pathways for both the degradation of pollutants and synthesis of valuable biomolecules. These technologies open new frontiers in bioremediation, bioplastics, and agricultural bio-products. The analysis highlights key achievements, promising technologies, and future development areas essential to sustainable development. By integrating microbial capabilities with cutting-edge biotechnology, the circular bioeconomy offers a path to reduce environmental impact, conserve resources, and build resilient production systems for a more sustainable future.

In Chap. 16, McKinney and collaborators address the challenge of bioplastic and its application to agriculture. Agriculture heavily relies on plasticulture, mostly Polyethylene (PE). While it is cost-effective and durable, it is poorly biodegradable. Biodegradable plastic mulches (BDMs), but their adoption is limited by higher costs, mixed results in yield and weed control effectiveness, and some environmental concerns. Strategies to improve the sustainability of BDMs include enhancing mechanical properties, reducing production costs, and improving biodegradability across environments. Improved BDM quality and reduction in their cost; combined with regulatory support, public awareness, and investment in recyclable or compostable alternatives—is essential to reducing negative environmental effects of plastic waste in agriculture.

In Chap. 17, Ventura and collaborators explore the application of biotechnology in urban settings. Urban areas, which account for over 70% of global carbon emissions and resource use, are central to climate change mitigation. Emissions can drastically be reduced by transitioning from linear to circular systems, emphasizing biological cycles, renewable resources, and minimized energy use. By using examples, the authors show the gain from applications such as anaerobic digestion, composting, and urban biorefineries for food-waste valorization and nutrient recovery. They also emphasize the demonstration of optimization models, such as system

dynamics and multi-objective programming, for helping simulate land-use scenarios and inform low-carbon urban design.

In Chap. 18, Cao and collaborators explore how advanced AI technologies can transform the circular bioeconomy (CBE). CBE integrates renewable biological resources and circular economy principles to reduce waste, regenerate ecosystems, and enable sustainable economic growth. Major AI applications in the CBE include: (1) generative design of novel bio-products and materials, (2) system simulation and predictive modeling for supply chains and bioprocesses, (3) intelligent automation and process control, (4) knowledge management and decision support, and (5) stakeholder engagement through multilingual bots, personalized dashboards, and automated project coordination. However, the deployment of AI in the bioeconomy must be approached cautiously, ensuring alignment with ecological sustainability, ethical integrity, and social equity.

In Chap. 19, Morgan and Miller present an integrated vision of sustainable development by aligning the One Health framework with the principles of the Circular Bioeconomy (CBE). One Health emphasizes the interdependence of human, animal, plant, and environmental health, while the CBE promotes sustainable use and regeneration of biological resources through circular systems that reduce waste and environmental impact. Five pillars essential to implementing a One Health-centric CBE: healthy environments, microorganisms, plants, animals, and humans. The chapter identifies practices that are essential for the integrated visions including: integrated livestock management, reduced synthetic inputs, equitable access to nutrition, climate-smart technologies, and integrated land and water management. Enhancing the adoption of system thinking, circularity, and one health will lead to adoption of the integrated vision.

In Chap. 20, Zilberman and collaborators present macroalgae (seaweed) as a promising but underutilized component of the bioeconomy, with potential applications in food, health, energy, and climate mitigation. Currently valued between $12–17 billion, the global macroalgae sector is projected to reach $35 billion by 2032. Macroalgae are used in food and beverage applications, hydrocolloids like agar, carrageenan, and alginate, production of pharmaceuticals, biofuels, bioplastics, textiles, agriculture (as biostimulants and animal feed), and carbon sequestration. Only about 50 species are commercially cultivated out of 72,500 identified algae species, pointing to vast untapped biodiversity. The macroalgae sector, if strategically supported, could become a cornerstone of the sustainable bioeconomy, with potential to exceed $100 billion in value. Success depends on coordinated investment in science, infrastructure, circular supply chains, and inclusive governance.

In Chap. 21, Wells Roland-Holst and Zilberman explore the transformative potential of biomass energy to address climate change, rural development, and energy equity—especially in California. Bioenergy innovation can displace fossil fuels, reduce wildfire risk by repurposing hazardous biomass residues, and support decentralized rural energy systems. California, with over 50 million bone dry tons of annual biomass waste, has vast potential for biomass conversion. These residues—ranging from forest waste to agricultural and municipal solid waste—could

be transformed into clean energy and valuable products while mitigating GHG emissions and fire risk. Economic benefits are especially compelling for rural communities, which often have high biomass density but low incomes. Adoption can be enhanced by modifying California's Low Carbon Fuel Standard (LCFS) to reflect in-state co-benefits—like fire prevention and rural job creation—not just GHG reductions.

In Chap. 22, Zhu and collaborators present an overview of China's bioeconomy transition. Since the 1980s, China has embedded biotechnology into its Five-Year Plans. The 14th Five-Year Plan (2021–2025) formally established bioeconomy as a national priority. The main sectors of the Chinese bioeconomy include biomedicine, driven by an aging population, rising healthcare demand, and expanding biopharma developments. Bio-agriculture focuses on food security and sustainability. Biomanufacturing produces fermented products, bio-based chemicals, and materials at scale. Bioenergy grows slowly but steadily. Environmental Protection applies biotechnology to waste management and a fast-rising Bioinformation and Biomedical Engineering sector. The development of the sector benefits from strong policy and financial support and increases the demand for sustainable solutions and rapid breakthroughs in synthetic biology, genomics, and precision medicine. However, challenges include global competition and geopolitical tensions, biomass feedstock constraints and energy inefficiencies, low consumer acceptance of genetically modified (GM) foods and bio-based products, and stringent GM regulations and public skepticism.

1.3 Case Studies in Latin America

The development of the bioeconomy has been emphasized in Latin America due to a combination of natural endowments, economic development needs, environmental challenges, and global policy trends. The region views the bioeconomy as a strategic path to sustainable growth, rural development, and climate resilience and this section of the book provides some case studies.

In Chap. 23, Kirschbaum and collaborators explore innovations in Argentina aimed at transforming fruit and vegetable (FV) waste into valuable bio-based inputs within a circular bioeconomy framework. The approach emphasizes three aspects. First, waste utilization is illustrated through composting practices in wholesale markets and FV processing plants. Second, biotechnological approaches to enhance native biological resources, including biopesticides. Third, wind and solar energy are used to support strawberry cultivation in harsh environments. The authors advocate for coordinated public policies, increased investment, stakeholder collaboration, and broader industry engagement.

In Chap. 24, Moriena and Zibell explore how Adecoagro, a Latin American agribusiness company, has integrated circular bioeconomy principles into its dairy operations to achieve sustainability across environmental, economic, and social

dimensions. Central to Adecoagro's model is the use of **biodigesters** that convert cow manure into renewable bioelectricity and biofertilizers. The company owns high-productivity dairies that benefit from integrating advanced technologies, such as cow monitoring systems, robotic milking, and solar energy. The company implements no-till farming, crop rotation, and cover cropping to improve soil health and productivity. This case study demonstrates the financial viability of circular agriculture, recognizing that the financial investment required may limit replication for smaller dairies.

In Chap. 25, Paes and collaborators introduce the concept of Circular Sociobioeconomy (CSBE) as a framework that merges circular bioeconomy principles with the cultural, ecological, and economic realities of the Amazon. Unlike conventional bioeconomy and circular economy models that emphasize efficiency and resource reuse, CSBE embeds these within the sociocultural practices of Indigenous Peoples and Local Communities (IPLC), making it more inclusive and sustainable. Two key case studies illustrate CSBE in action: the community co--management of Pirarucu (the Amazon's largest freshwater fish) and the production of cosmetic oils from andiroba and murumuru seeds. These activities involve local families, reinforce traditional knowledge, and utilize biowaste in cascading and regenerative cycles—for example, fish scales for jewelry, skin for leather goods, and oil residue for soap. These circular practices support livelihoods, strengthen cultural identity, and contribute to biodiversity conservation.

In Chap. 26, Barelli and collaborators explore the implementation and potential of circular economy (CE) practices in Argentine agribusiness through a producers' network. The network—comprising over 2000 producers—has played a central role in this transition by fostering collaborative learning and innovation. The initiative followed three stages: establishing a locally adapted definition of circular bioeconomy; surveying and analyzing adoption patterns within network; and designing tools to enhance adoption. Circularity was defined as reducing, reusing, and recycling materials across biological and technical cycles to promote sustainable agribusiness and regional resilience. Survey results from 2023 revealed that 22% of producers had already implemented CE practices, with another 51% expressing future intent. Adoption was particularly strong in intensive livestock systems (e.g., pigs and dairy), and common practices included effluent reuse and renewable energy generation. Key drivers were environmental benefits (54%) and economic incentives like cost reduction and value addition. Barriers included high investment costs, limited access to finance, and inadequate training.

In Chap. 27, Dürr and collaborators examine the evolving role of forest-based bioeconomy strategies in the Brazilian Amazon, particularly those centered around non-timber forest products (NTFPs). The chapter identifies new opportunities arising from recent technological advances—biotechnology, digital tools, and sensing/robotics—which have the potential to enhance product development, improve market access, reduce environmental impact, and streamline value chains. However, these innovations could also reinforce existing inequalities and ecological risks without appropriate regulations. Empirical evidence reveals mixed outcomes. While

initiatives like açaí production have generated significant economic benefits, they have also caused ecological degradation and reinforced social inequities. Key lessons include the need for inclusive governance strategies that anticipate and manage the social and environmental consequences of market integration and technological adoption.

In Chap. 28, Noriega and collaborators examine the potential of sugarcane as a key enabler of the circular bioeconomy in Latin America. Sugarcane, cultivated over 12 million hectares in the region, supports approximately 6.4 million jobs and contributes significantly to exports and renewable energy. Circular practices led to notable advancements including reducing water consumption by up to 85% in São Paulo mills, the use of software and sensors for irrigation optimization, and wastewater reuse for fertigation. Biofertilizers—based on nitrogen-fixing bacteria—are increasingly replacing synthetic inputs. Electricity from bagasse powers mills and supplies national grids, accounting for 30% of Guatemala's energy during harvest. Ethanol production offers a low-emission alternative to fossil fuels. Yet, there are needs for broader adoption of best practices across the region, enhanced investment in R&D, capacity building, legal certainty, and integrated governance. The future pathway calls for leveraging sugarcane's full bioeconomic potential through product diversification—including bioplastics, biochar, and sustainable packaging—and life cycle assessments to measure impacts.

1.4 Conclusions

The bioeconomy holds significant promises for addressing grand societal challenges such as climate change, biodiversity loss, and rural underdevelopment. Achieving the potential of the bioeconomy requires a transition to circular and regenerative models, which integrate technological, economic, and ecological dimensions. Transition to a circular bioeconomy requires coherent policy and political will, investment in R&D, infrastructure construction, and effective regulation and institutional reforms. Government policies need to enhance private sector engagement by inducing investment and establishment of supply chains that embody circularity. The growth of the bioeconomy will benefit from regional, national, and international collaborations, and will enable and enforce circularity and sustainability. Despite promising examples, the bioeconomy is still in a nascent phase, with uneven adoption across sectors and geographies.

Similarly, the research about the bioeconomy is about uncertainty. There is a need to develop theoretical and empirical models to integrate circularity with regenerative principles, particularly in agriculture, forestry, and urban systems. Advanced research is needed to expand the frontier of knowledge about bioeconomy potential, in particular, research on underutilized biological resources (e.g., macroalgae, insects, and microbial consortia) and their biotechnological applications in food, materials, and energy. Research on the design of and assessment of the performance of the supply chain, especially one that incorporates circularity, and sustainability is

a major priority. One area of emphasis is the Climate-Bioeconomy Nexus, expanding research on how bioeconomy systems contribute to mitigation and adaptation strategies, including carbon sequestration, landscape resilience, and climate-smart practices.

Bioeconomy research should have a strong policy and economic component to allow Better understanding of the impact of alternative institutions and policies on the emergence of the bioeconomy, both in terms of innovations, products, supply chains, and income distribution will be important for policy design. There is a need to study how bioeconomy strategies can be adapted to serve marginalized communities, including mechanisms for capacity building, equitable value distribution, and participatory governance. We need to further develop bioeconomic metrics and indicators to improve tools for evaluating bioeconomy systems—including multi-criteria sustainability assessments, carbon accounting, and socio-economic impact measurement. Finally, the bioeconomy should not be limited to the rural sector. Urban bioeconomy and circular cities study the design and operation of urban bioeconomies, including decentralized biorefineries, food-waste valorization, and infrastructure for nutrient and energy recovery.

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Chapter 2
Circular Bioeconomy Systems: A Path Toward a Sustainable Future

Brahm P. Verma and James W. Jones

The current economy is composed of both linear economy systems (LES) and circular economy systems (CES). It includes both fossil resource-based and biomass-based economy systems. Thus, the current economy system is a combination of linear-fossil-based-, circular-fossil-based-, linear-bio-based-, and circular-bio-based-economy systems. Figure 2.1 shows that the current economy is predominantly a linear, fossil-based economy system, and also illustrates the goal to grow the overall total economy into a total economy in which circular bioeconomy systems are dominant portions of the future economy.

Linear Economy System (LES) is referred to as the *take-make-use-dispose* economy system in which resources move in one direction—from raw input resource materials to make, use, and waste.

Circular Economy System (CES) is referred to as the *take-make-use-reuse* economy in which resources are captured from the after-use materials and loop back to minimize waste and pollution.

Fossil-based Economy System (FES) is the economic space in which Earth's stored resources (coal, petroleum, minerals, and water from aquafers) are the raw input resource materials.

Bio-based [Bioeconomy] Economy System (BES) is the economic space in which products, processes, and services are derived from renewable biological resources (e.g., plants, animals, and microorganisms).

Circular Bioeconomy System (CBS) is the economy system that interweaves designed biosystems with Nature's ecosystems for renewable biological materials

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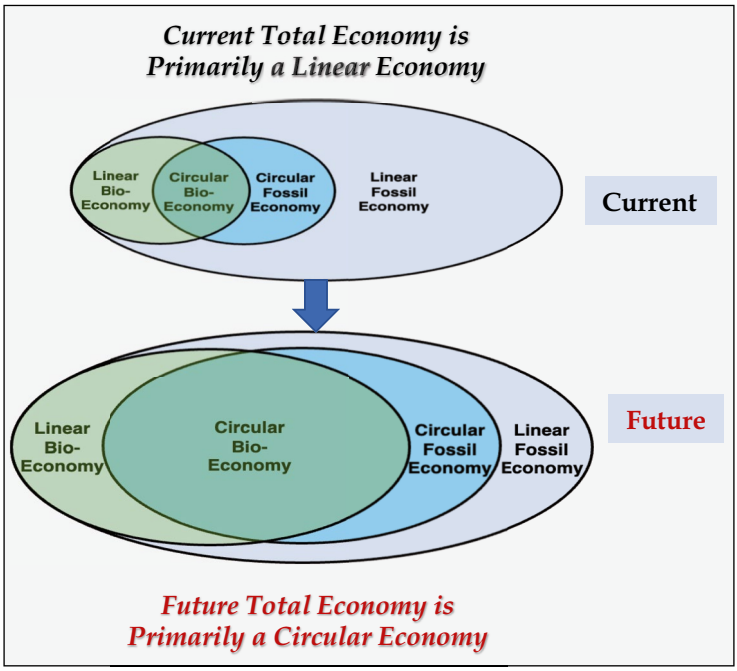


Fig. 2.1 Components of the current economy system, which is a combination of linear-, circular-, fossil-based-, and biomass-based-economy systems

and human-made socio-economic systems, and in which resources from after-use materials are captured and looped back for reuse toward producing zero waste.

The current U.S. economy system is predominantly an unsustainable fossil-based LES. It depletes finite resources, produces vast amounts of wastes that pollute natural resources, degrades health of Earth's ecosystems, and contributes to climate change. To move toward a sustainable future, the overall goal is to transition the LES to CES, replace FES with BES, and make CBS the dominant component of a new, larger and more profitable, resilient, and sustainable economy.

This chapter briefly presents overall perspectives on the urgency to adopt principles of circularity for transitioning to circular systems, explains the bioeconomy as a complex bio-, eco-, and socio-economic-system of systems, and highlights the importance of developing transformational strategies for use-inspired multidisciplinary research and technological innovations to provide system-level solutions for meeting the grand challenges facing the 2050 world.

Nature's circularity is formed by its biochemical processes at molecular-, cellular-, organism-, landscape-, and global-levels powered by solar energy that sustains the Earth's resources for human needs, and drives economic activities. These processes are interwoven over space and time, and together interact and adopt to changing conditions to provide ecosystem services and products for living systems. By harnessing and modulating these biochemical processes, humans have created

biosystems to produce food, feed, fuel, and other materials for human needs (Fig. 2.2). Verma (2025) stated that biosystems include agriculture, forestry, aquaculture, bioreactors, and any other systems with biological activities that provide products for human needs and ecosystem services for economic and environmental sustainability.

Biogeochemical cycles that recirculate resources are comprised of many circular systems and produce no waste. Morton and Shea (Morton & Shea, 2022) describe these as *Circles of Life* (Fig. 2.3). "One organism's waste is another organism's food, and nutrients and energy flow in loops of growth, decay, and reuse." Circular biosystems that model the circle of life, *take-make-use-reform-recapture* Earth's resources, can form an economy system that captures lost resources, minimizes wastes, provide ecosystem services, and increase economic profitability.

Humans survive using the fruits of the Earth's ecosystems powered by the energy from sun. In the beginning, with small populations distributed over vast landscapes and with limited physical abilities to access and use resources, humans lived in a near perfect circular system in which used resources were either recycled through ecosystems or fossilized and stored in the Earth over millennia. This balance has been increasingly disrupted as biosystems evolved by increased knowledge of biological processes and use of advanced technologies to modulate processes for maximizing productivity and profitability. These advances have served societies well in the past to meet ever-increasing demands by the rapidly growing global population that is increasingly concentrating in urban metropolis areas that demand high-quality food, goods, and services. Supply chains for managing flows of food and other biomaterials to support cities produce massive amounts of wastes that are discarded in huge quantities in landfills from where liquid and gaseous products of decomposed organic wastes contribute to GHG emissions, transport pollutants into water resources, and degrade quality of air, land, and water resources.

The current bioeconomy is largely linear (Fig. 2.4) and a product of genetic modifications for modulating biochemical process of constituent biosystems and innovations in engineering and information technologies. It focuses on optimizing

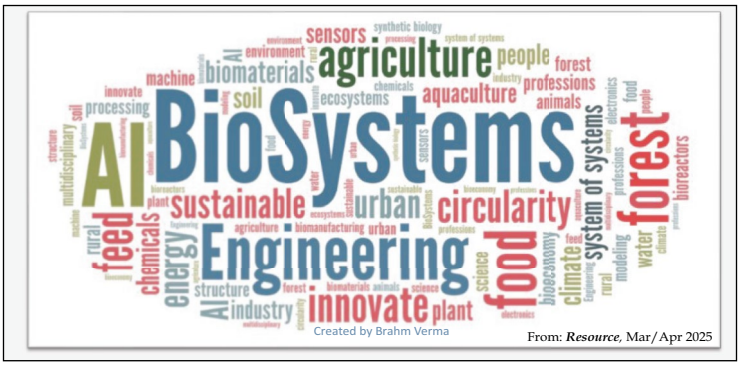


Fig. 2.2 Biosystems use natural resources whose products are synthesized by modulating biological processes for useful purposes

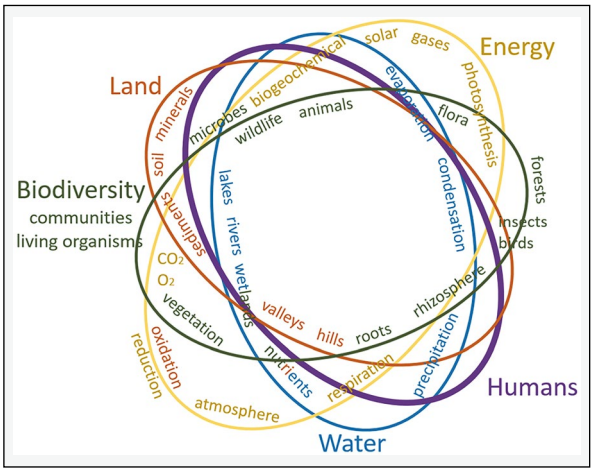


Fig. 2.3 Circles of life in natural world include many dynamic interwoven processes over space and time. From: Morton and Shea (2022)

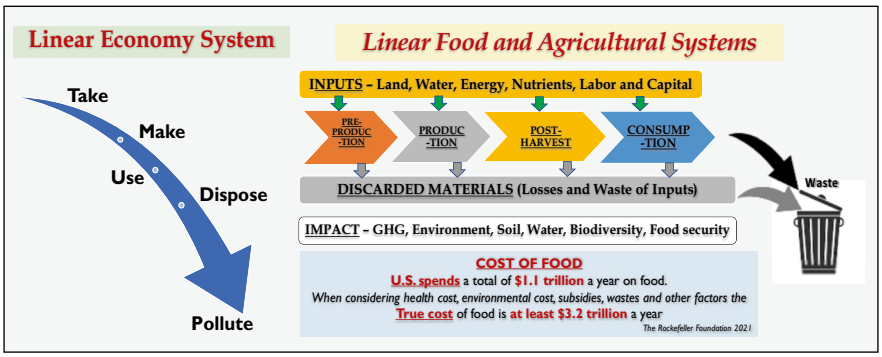


Fig. 2.4 Left figure shows the flow of energy and materials in a linear economy system that discards resources and produces waste. Right figure shows linear bioeconomy (agri-food) systems in which nearly two-third value of the input resources of the entire value-chain is lost when considering health cost, subsidies, and waste costing nearly $2.1 trillion a year. From: Verma and Jones (2025)

functions of each constituent system to improve productivity and profitability. These advances have led to a food and agriculture economy system that is largely linear (*take-make-use-waste*) and heavily dependent on fossilized resources. In a linear *one-way flow of mined resources* economy, fossilized resources stored over millennia are consumed beyond the Earth's capacity to renew them. On one hand, driven by innovations in genetics, agronomy, mechanization, informatics, and other fields of science and engineering, expansive use of land and natural resources (e.g., fresh water, nutrients), and policies enabling productivity and profitability, these linear biosystems in the last 100 years have quadrupled the supply of food, fiber, and other bioproducts and reduced global poverty and hunger to historically low levels. But on the other hand, the disruption of natural cycles has resulted in massive amounts of wastes and GHG emissions that pollute our soils, water, air, and ecosystems,

depleting their capacity to provide resources for future generations and adversely contributing to climate change. The Food and Agricultural Organization (FAO) of the United Nations (UN) estimated that the global food and agriculture sector contributes about 31% of human-caused greenhouse gas emissions (21% of all global CO_2, 53% of all methane, and 78% of all NOx), and that over one-third of all food grown in the world is wasted. A 2021 Rockefeller Foundation study estimated that, when considering human health cost, environmental cost, subsidies, waste, and other factors, the additional cost to the U.S. economy is at least $2.1 trillion a year.

We have entered a critical phase questioning the Earth's capacity to provide resources needed to feed future generations. It requires that, in the next quarter century, when the 2050 global population has increased by nearly 33% to reach over 10.7 billion, we must transition into a circular bioeconomy system that can meet the following challenges:

- Increase food supply by 70%
- Increase availability of biomass to replace fossil-based feed stock for biomanufacturing, in addition to providing needed food, feed, fiber, and bioenergy
- Drastically reduce GHG emissions, nutrient losses, and pollution
- Increase sequestration of carbon in soil
- Increase economic opportunities for rural areas
- Improve resource use efficiency by an order of magnitude to account for, on a per capita basis, over 30% reduction in availability of Earth's resources (fresh water, arable land, fossil-fuel based energy, and chemicals)
- Develop strategies and upgrade supply chains to meet needs of an urbanized global population (with nearly 75% people living in urban areas) and
- Build resiliency to adapt to unexpected events and climate change

Bioeconomy systems are intertwoven human-managed biosystems, Nature's ecosystem, and human-made social economic systems as illustrated in Fig. 2.5. Their patterns of relationships form complex networks of systems of systems to produce biomass on land, in water, in laboratories, or elsewhere; synthesize new products, chemicals, and materials for human needs (e.g., food, feed, fiber, fuel, chemicals, and more); provide eco-service to sustain natural resources; and become sources of economic profitability.

Currently, decisions in bioeconomy systems are often made to address problems of a single constituent system ignoring interdependence and interrelationships with other constituent systems. These decisions have created a myriad of unintended outcomes, e.g., produce wastes that pollute and adversely affect the health of Earth's ecosystems and the quality of natural resources. Additionally, the current bioeconomy system gives a false impression of its productivity and profitability by excluding subsidies, the health costs, environmental costs, and natural resource quality costs, in the price of biosystems products (Shah, 2021).

Resource use efficiency in the current economy is largely a product of physical devices with precision technologies and informational sciences for timely management decision. However, Nature's tools are largely living organisms performing biochemical processes, and using molecular machines to perform desired functions.

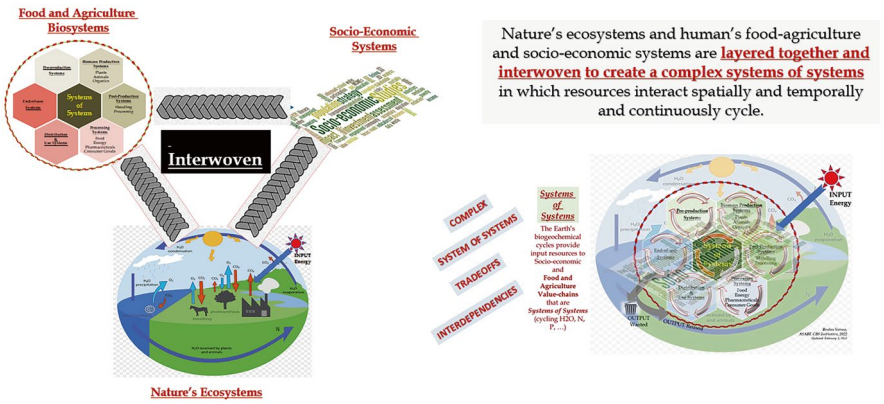


Fig. 2.5 Illustration of the bioeconomy as complex intertwoven systems of systems. Figure on the left shows that biosystems, nature's ecosystems, and human-made socio-economic systems are interwoven. Figure on the right shows that these three systems are also layered and networked. In complex systems of systems, bioeconomy system actions in any part of the system must be made in the context of the performance of the whole system

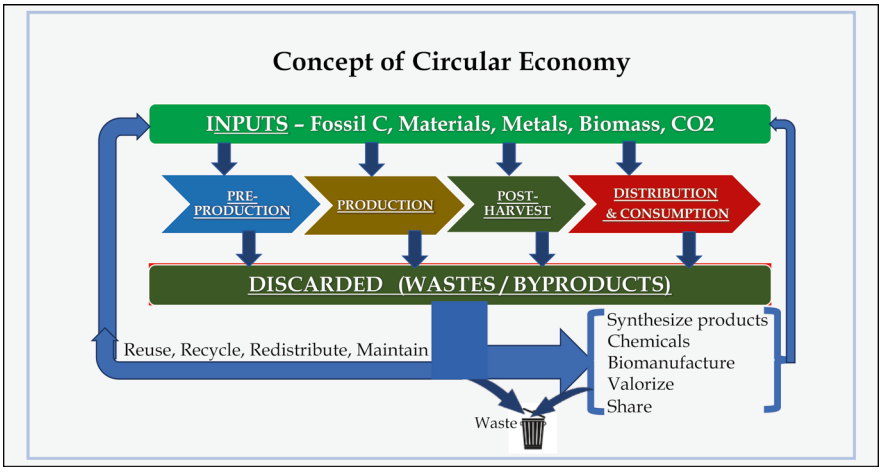


Fig. 2.6 Illustration of the circular economy concept in which resources embedded in discarded materials (wastes) are reused or captured to synthesize new value-added products and minimize waste

They keep products and materials in use for as long as possible; and one organisms' waste becomes another organisms' food, nutrient, and energy supplies, forming a circular loop of *take-make-use-decay-reuse*.

Circular economy systems (CES) could conceptually be created by mimicking Nature's cyclical processes where discarded wastes from all parts of the value-chain are captured and their resources are reused, recycled, and reformed for synthesizing value-added products and services, as shown in Fig. 2.6. These CES should reduce

wastes. Building on Ellen MacArthur Foundation three principles of circularity (Ellen MacArthur Foundation, 2019), the American Society of Agricultural and Biological Engineers (ASABE) added two additional principles (principles 1 and 5 listed below) to recommend the following five principles of circularity (Jones et al., 2024) for designing a circular economy system.

1. Increase resources use efficiencies to reduce input sources
2. Design out waste and pollution toward the goal of achieving zero waste
3. Keep products and materials in use within the system as long as possible
4. Regenerate natural systems and
5. Provide economic benefits as an incentive for adoption into general economy

A successful design that advances CES must positively satisfy all five principles of circularity and show overall reduction in waste toward zero waste.

Circular Bioeconomy System (CBS) is the portion of CES in which products, processes, and services are derived from biological materials. It will require using the five principles of circularity and replacing fossil-based resources with renewable biological materials to transition the linear and circular non-biobased economy to CBS. Figure 2.7 shows a conceptual model of CBS illustrating the flow of biological materials throughout the value-chain and lists techniques for capturing resources from products that are discarded as waste. It also lists needs of knowledge development and innovations for making the transition.

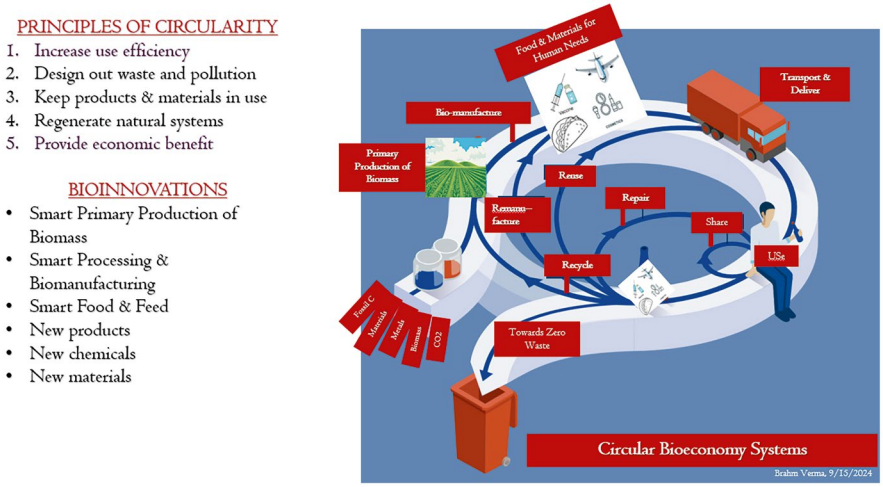


Fig. 2.7 A conceptual model of CBS illustrates the flow of biological materials throughout the value-chain, and a range of products (e.g., food, pharmaceutics, cosmetics, fuel, and others) and processes developed by using the five principles of circularity toward zero waste. New knowledge and techniques will be needed to innovate bioproduction, bioprocessing, and biomanufacturing for synthesizing new products, chemical and materials and toward zero waste

Bioeconomy, based on renewable biological materials, is a complex system of systems. As illustrated in Fig. 2.5, bioeconomy is an interwoven system of interconnected and interdependent constituent systems forming patterns of relationships that dynamically respond and adopt to changing conditions. The study of a bioeconomy requires integrated observations from biological, physical, geological, and behavioral and social sciences perspectives. The U.S. National Academies of Sciences, Engineering and Medicine (NASEM) reported (National Academies of Sciences, Engineering, and Medicine, 2020) that advances in the bioeconomy will be driven by convergent scientific research, and enabled by technological innovations shown by four gears in Fig. 2.8. Adding the fifth gear (shown on top in Fig. 2.8) recognizes the critical need to understand the role of social, cultural, policy, and human behaviors in the adoption of advances to replace unsustainable fossil-based carbon with the renewable biological materials feedstock.

Development of knowledge, techniques, and skills will require ***transformational actions*** in which individuals and organizations should come together to form processes, structures, and adaptive networks of multidisciplinary-stakeholder teams. These teams should collaboratively engage in convergent science and practicable

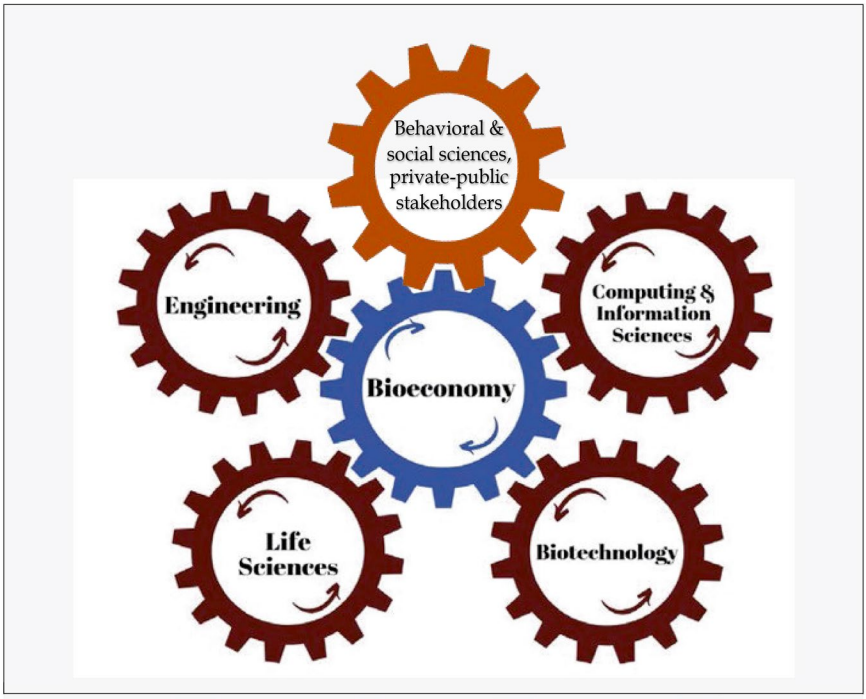


Fig. 2.8 Drivers of bioeconomy systems' activities are shown by four brown wheels (National Academies of Sciences, Eengineering, and Medicine, 2020), and the fifth wheel on the top, added by the ASABE Task Force (Migliaccio el al., 2023), represents the importance of human behaviors in the adoption of new technologies

innovations to address problems that will enable transition to sustainable circular systems across the entire value-chain.

Transformational actions to transition food and agricultural systems to circular systems were initiated by ASABE in 2020. In its first action, a 23-ASABE members roundtable (Nokes & Jones, 2021) explored the complexities and obstacles to transitioning the following biosystems into circular systems: (1) Corn-soybean production systems, (2) Open-field systems for fresh-market tomatoes, (3) Controlled biology-based indoor food systems, (4) Controlled-environment plant production systems, (5) Animal production and processing systems, and (6) Pork supply chain systems. One of the major conclusions was the need for disciplinary professional societies to come together to innovate system-level solutions for overcoming obstacles for transforming to circular systems.

In its second actions, a 36-member focus group representing 14 disciplines and 4 stakeholder groups addressed the question: *What auctions should professional societies take, within themselves and together with other professional societies, that would lead to broad adoption of circularity as a strategy to transform food and agricultural systems, improve efficiency and sustainability, and meet the anticipated 70% increase in global food demand by 2050?* The four strategic recommendations of the focus group were: (1) Build network(s) to communicate and collaborate with multiple societies, (2) Develop multi-society R&D goals for a shared path to circularity, (3) Engage prominent organizations to serve as catalysts in multi-society R&D, and (4) Develop multi-society educational materials and host outreach and training workshops (Verma et al., 2021).

In its next bold action, ASABE appointed a Task Force that created three working groups to (1) develop messaging documents that will clearly describe and effectively communicate the importance of circularity as a potential path toward sustainability and meeting upcoming challenges, (2) recommend ways ASABE should restructure to incorporate circularity in its DNA, and (3) draft a plan for connecting and bringing together professional societies into an alliance that includes collaborative activities, programs, projects, and services to develop convergent science and engineering knowledge to transform systems that underpin a new circular bioeconomy (Migliaccio et al., 2023).

Working group 1 of the Task Force developed the five principles of circularity discussed earlier and organized numerous webinars and presentations that engaged multiple professional societies, stakeholder groups, including the National Academy of Science, Engineering and Medicine. Without exception, all responses expressed support and expressed desire to join the ongoing efforts to advance CBS. ASABE website (https://asabe.org) has records of the messaging documents and organized activities.

Working group 2 of the Task Force studied the limitations of current ASABE structure for addressing needs for advancing CBS. It helped form a semi-autonomous Circular Bioeconomy Systems Institute (CBSI) within ASABE. The CBSI is organized to be a catalyst for building alliances/partnerships, and supporting and sustaining multidisciplinary teams to address problems and create system-level solution to advance CBS. Its structure and management schemes are modeled after the

findings of working group 3 described below. The CBSI encourages any interested individual, including those who are not an ASABE member to join and fully participate in its activities. For additional details visit https://cbsi-asabe.org

Working group 3 engaged 26 members that included leaders of eight professional societies including five members of the US National Academy of Science, Engineering and Medicine (NASEM), foundation presidents, and stakeholder representatives. It developed a model alliance of multidisciplinary professional society (Fig. 2.9). It is patterned to capture key features of a *Joint Venture* that would provide mechanisms for members to self-organize into multidisciplinary teams to develop knowledge and innovative system-level solutions for problems of constituent systems in the context of the whole economic system. The model alliance also provides opportunities for members to identify and prioritize problems. Its two major objectives are to promote universities, research laboratories, and industries to form and participate in local, regional, national, and global networks of multidisciplinary working teams, and to leverage agencies, foundations, and industry to provide resources to fund programs. It is also important to observe that in this creative environment each participating discipline will develop its own disciplinary knowledge in ways not possible otherwise. In a way, the concept of the model alliance shown in Fig. 2.9 can be viewed as a multidisciplinary professional society to attract a global community of innovators who self-organize to form working teams,

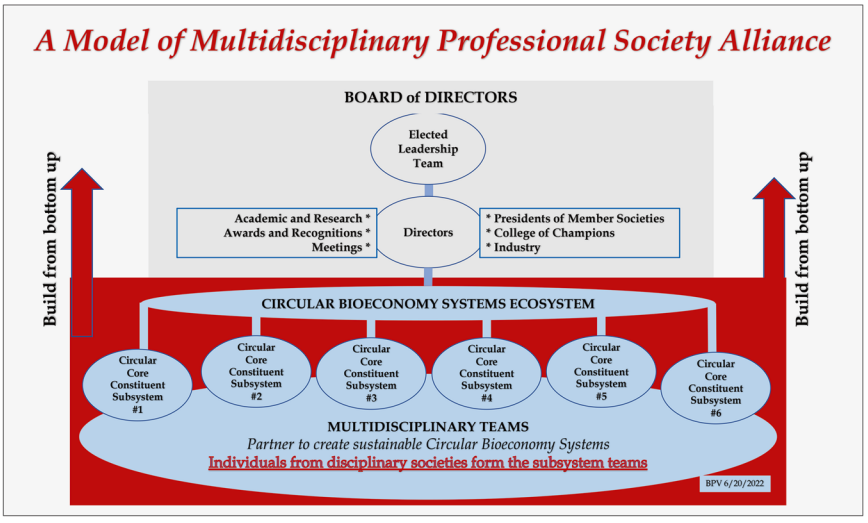


Fig. 2.9 A model of multidisciplinary professional society alliance is a Joint Venture with participating disciplinary professional societies. The top block (in gray) illustrates the operating and executive functions, and the bottom block (in red) shows several organized and self-organized multidisciplinary working teams formed by members of institutions, agencies, foundations, and stakeholders. The two red arrows pointing upwards signify that the formation of the alliance should begin from bottom, that is, first form several multidisciplinary teams to innovate solutions and from their experiences refine the operating and executive structure

integrate knowledge, experiences, and perspectives of disciplines and public and private sectors for studying existing bioeconomy systems and identifying technologies, methods, and policies needed to transform them to more circular bioeconomy systems. Furthermore, the model alliance can lead in implementing system-level solutions to advance toward sustainable CBS.

To prototype the model alliance for assessing its feasibility and performance, eight 2-day workshops were organized that hosted 25–35 invited participants from diverse disciplines and experiences, and engaged them in intensive brainstorming and educational activities to explore needed knowledge, techniques, and skills to advance toward sustainable CBS. In total, over 240 individuals representing scores of disciplines and public-private sectors participated in these workshops, and provided key insights that supported our envisioned path toward transitioning into sustainable CBS. The overall outcomes of the workshops confirmed that collaborative participation by individuals and organizations; developing networks that integrates expertise, perspectives, and goals; and adopting shared cultural norms are strategically important for achieving desired goals. There was a strong sense that building of an alliance should take a bottom-up approach; that is, start by first catalyzing self-organized multidisciplinary teams focused on innovating practicable solutions for a select part(s) of the value-chain, and then using their successes, engage leaders of the teams to refine operative and executive functions and structures of an alliance envisioned and shown in Fig. 2.9.

In its yet another bold move, and to implement the bottom-up approach, ASABE formed the semi-autonomous CBSI to incorporate features and functions of the conceptual alliance. Figure 2.10 shows the CBSI governing structure where working

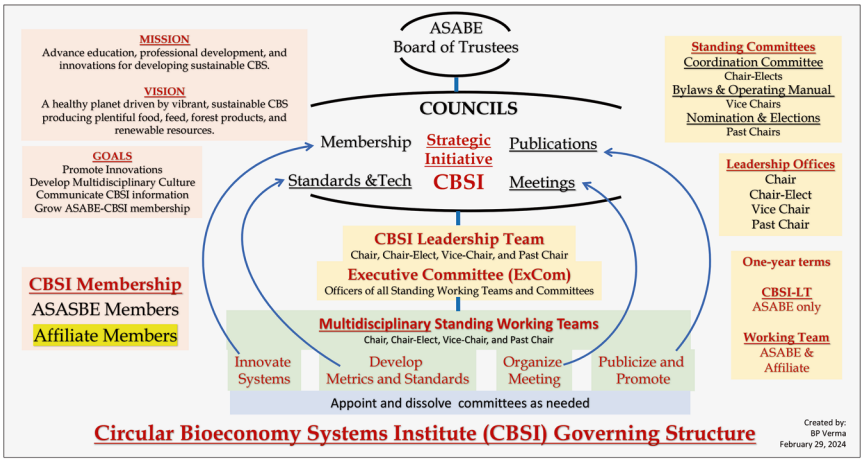


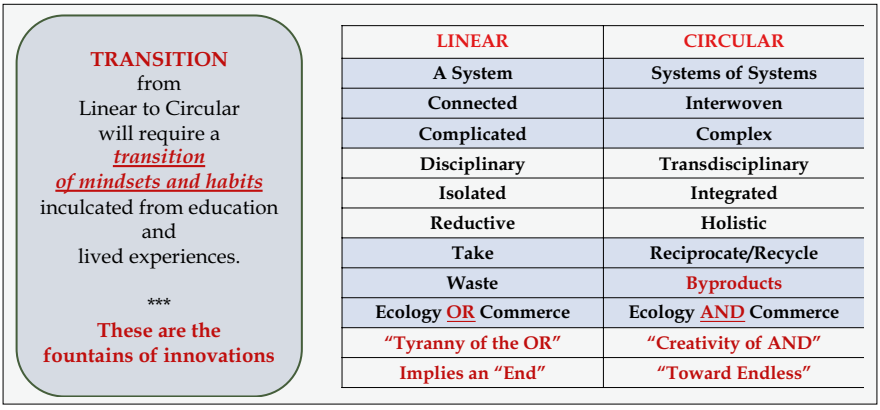
Fig. 2.10 The governing structure of the Circular Bioeconomy Systems Institute (CBSI) and its mission, vision, and goals. The four multidisciplinary teams provide leadership for forming working groups to innovate, develop metrics and standards, organize meeting, and publicize and promote the work of CBSI. Members of CBSI, who are not ASABE members, are designated as "Affiliate Members" and fully participate in all roles in the Working Teams

teams are strategically connected to receive support from the leadership and services from the executive and operational structure of ASABE.

CBSI solicits broad participation by individuals without requiring them to be ASABE members. It also solicits other professional societies/organizations to fully engage in CBSI and provide leadership toward forming an alliance. CBSI is organized into four working teams to: (1) Innovate Systems and System-level Solutions, (2) Develop Metrics and Standards, (3) Organize Meeting and Conferences for in-person and virtual participations, and (4) Publicize and Promote the advances toward CBS. These teams provide the core functions required for fulfilling the purpose of an alliance, which must be enthusiastically fostered by executive leadership, and supported by unencumbering operational processes. These teams must accommodate perspectives and methods of partnering organizations. ASABE amended its Constitution, and modified it executive leadership structure and operational processes to provide CBSI autonomous privileges, where CBSI is serving as a society within a society to build multidisciplinary alliances.

Ultimately, transitioning to a more sustainable CBS will require transition of mindsets and habits inculcated from educational and lived experiences. They are the lens through which we make observations, formulate problems, develop methods to gain deeper understanding and insights, innovate solutions, develop policies, and make decisions for short- and long-terms outcomes. Figure 2.11 shows that our current mindsets and habits favor reductionist thinking in which "OR" is the operative function. For example, a system can be economically profitable OR provides ecosystem services to sustain the environment, but not both.

Haken (2006) in his book *The Ecology of Commerce* presents strong evidence that commerce is a path to sustainability of ecosystems, and all engineered systems must eloquently imitate nature's circularity. "Companies must re-vision and re-imagine themselves as cyclical corporation, and businesses can find the shortest,



LINEAR	CIRCULAR
A System	Systems of Systems
Connected	Interwoven
Complicated	Complex
Disciplinary	Transdisciplinary
Isolated	Integrated
Reductive	Holistic
Take	Reciprocate/Recycle
Waste	Byproducts
Ecology OR Commerce	Ecology AND Commerce
"Tyranny of the OR"	"Creativity of AND"
Implies an "End"	"Toward Endless"

Fig. 2.11 Lists depicting transitions in thinking elements to create mindsets and habits in individuals and organizations for innovations and actions to advance sustainable circular bioeconomy systems

simplest ways between the earth, the hand and the mouth that are restorative to society and the environment." Our civic and technical educational systems must play a major role in modifying behaviors and cultural norms, so they become guides to actions in all walks of life toward forming sustainable circular systems.

In summary, we present the following perspectives and actions for meeting the challenges for 2050:

- Transition the current liner economy to a circular (*take-make-use-reuse)* economy system by adopting the principles of circularity that mimic Nature's *Circles of Life* to move toward zero waste
- Find ways to replace fossil-based resources with biological materials, and grow biomanufacturing to make it the predominant part of the economy providing for all human needs, and meeting global sustainability goals
- Organize multidisciplinary teams that integrate perspectives of disciplines and adopt system-level thinking for innovating solutions in the context of the whole system. Problems of complex systems cannot be addressed by a single discipline or by focusing decisions to improve performance of component systems in isolation
- Form a network(s) of multidisciplinary teams that models patterns of relationships of complex systems for unraveling mysteries for developing practical solutions
- Create a professional society alliance(s) that becomes a home for global community of innovators and a catalyst for building networks that lead in implementing system-level solutions to advance toward sustainable CBS and
- Transition mindsets and habits of individuals and organizations through education and living experiences where all engineered systems eloquently imitate nature's circularity

In conclusion, transitioning to a sustainable circular bioeconomy system is an important and immediate need to provide for human needs, and protecting the Earth's ecosystems and natural resources. This effort will be a marathon, not a sprint, and it will take all hands-on deck. So, let's join hands and get started now.

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Chapter 3
Building a Better Bioeconomy, from the Ground Up: Scaling Bioeconomy Development to Reduce Risk in Biobased Value-Chain Investments

Herrick Fox

3.1 Background: Defining the Bioeconomy

Definitions of the word "bioeconomy" vary. As understanding of the term continues to evolve, a practical and inclusive approach is to characterize the bioeconomy as the part of the economy that employs traditional knowledge and technological innovation in the utilization of biological resources and process to waste less, renew more, and support the resilience of ecological and socioeconomic systems to thrive within planetary limits. Origins of this understanding can be found in numerous bioeconomy initiatives around the world, such as in the High Level Principles on Bioeconomy adopted by the G20 in 2024, listing ten goals ranging from biodiversity and food security to climate resilience and valuation of traditional knowledge.7; in U.S. government parlance: "the part of the economy that is based on biological resources, processes and services";[1] and in the E.U.: "cover[ing] all sectors and systems that rely on biological resources (animals, plants, microorganisms and derived biomass, including organic waste), their functions and principles."[2] The term has also been defined with a strong focus on innovation, such as: "economic activity derived from the life sciences, particularly in the areas of biotechnology and biomanufacturing, including industries, products, services, and the workforce."[3]

These inherently broad scopes are more implementable when presented in goal-oriented terms, such as those offered by two "fathers" of bioeconomy in academia: "the sectors of the economy providing goods, services, and processes from biological resources, utilizing advances in life and information sciences to enable a

[1] The Bioeconomy: A Primer | Congressional Research Service.

[2] EU Bioeconomy Strategy (2018) | European Commission, DG-RTD.

[3] Bioeconomy Lexicon | National Institute of Standards and Technology.

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D. Zilberman et al. (eds.), *Handbook of Circular Bioeconomy*, Natural Resource Management and Policy 61, https://doi.org/10.1007/978-3-032-07112-5_3

transition from fossil fuels towards a renewable economy";[4] and "the production of renewable biological resources and their conversion into the 4 F's: Food, Feed, Fiber and Fuel."[5] Another goal-oriented description, notably succinct: "the goal of the bioeconomy is to transform the current economic system into an economy based on renewable resources."[6]

The International Advisory Council on the Global Bioeconomy blends all of the above: "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."[7]

3.2 Biobased Value Chains and the Transformative Potential of the Bioeconomy

Whatever the definition, the bioeconomy encompasses countless industries and sectors, from health care and food systems to energy production and manufacturing. Some parts of the bioeconomy, especially in biobased production,[8] are as ancient as agriculture itself. Others, namely biomanufacturing[9] and biotechnology,[10] are more recent with the advent of life-sciences discoveries whose transformative potential has been likened to the Industrial Revolution.

In light of this, the last three U.S. Presidential Administrations and other jurisdictions have commonly emphasized biotechnology and biomanufacturing as priorities for national and economic security. The use of biomanufacturing to produce biofuels such as ethanol, jet fuel (sustainable aviation fuel), and renewable natural gas is considered to be one of the greatest success stories in the modern global bioeconomy; as such it attracts robust private-sector investment.

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[4] Zilberman, David et al. (2024).

[5] Patermann, Christian (2021).

[6] Centre for the Bioeconomy | Universität für Bodenkultur (BOKU).

[7] https://www.iacgb.net/GLOBAL

[8] "A biobased product is a product determined by the Secretary to be a commercial or industrial product (other than food or feed) that is—(A) composed, in whole or in significant part, of biological products, including renewable domestic agricultural materials, renewable chemicals, and forestry materials; or (B) an intermediate ingredient or feedstock" 7 U.S.C. § 8101

[9] Biomanufacturing is defined in the NIST Bioeconomy Lexicon as the use of biological processes to produce goods and services at commercial scale. Though photosynthesis is a biological process (and thus would include biobased production), in practice the term refers more to the commercialized use of processes such as precision fermentation, transesterification, and genetic engineering.

[10] Biotechnology is defined in the NIST Bioeconomy Lexicon as technology that applies to and/or is enabled by life sciences innovation or product development

By contrast, biobased production, which relies more on mechanical and thermal processes, portends greater return on public-sector investment because there has been less development where biobased value chains offer the greatest potential to substitute renewable for non-renewable resources in the economy. As such, they are riskier investment targets for the private sector. The exponential growth that public investment can bring to these biobased value chains can more immediately support competitiveness, economic self-reliance, and rural development at larger scales while enhancing ecological and socioeconomic resilience throughout wide swaths of the economy.

The annual contribution of biobased products to the U.S. economy was estimated to be $489 billion in 2023.[11] Biobased production is also the key to reducing the risks of catastrophic wildfire on 242 million acres of highest-risk lands (46% private, 46% Federal, and 5% State) requiring immediate treatment throughout the USA,[12] threatening 115 million people and 48 million buildings nationwide.[13] Removing the massive quantities of woody biomass necessary to reduce this risk is not feasible without vastly expanded markets for the biobased products that can be made from it.

Therefore, it should come as no surprise to see more recent bioeconomy initiatives placing increased emphasis on building capacity in these value chains, such as in Executive Order 14081 in the USA (see below) and bioeconomy strategy revisions in the EU, G20, and FAO, to name a few. These initiatives demand robust leadership from academia not only in research, but also to objectively prioritize investments in value-chain capacity building and market development as well.

3.3 Toward A Practical Taxonomy of the Bioeconomy

Determining whether or not an activity falls within the scope of the bioeconomy depends on the goals of the beholder. If a basic goal of the bioeconomy is to transform the economy to one that wastes less and relies on renewable resources more, then the following framework has demonstrated practicality:

- Biobased production—Adding value through the use of non-biological processes (thermal, mechanical, digital) like pyrolysis, milling, and precision agriculture, such as for:
  - Building materials, e.g. mass timber, hempcrete, biochar as a concrete additive, etc.
  - Capacitors for batteries, e.g. plant-fiber capacitors.

[11] U.S. Dept. of Agriculture, Economic Impact Analysis of the U.S. Biobased Products Industry, Washington, DC, 2023.

[12] USDA Forest Service, Wildfire Hazard Potential of the United States, Washington, DC 2024.

[13] USDA Forest Service / wildfirerisk.org, 2024.

  - Energy via combustion or gasification, e.g. from wood pellets or biochar.
  - Natural resources used optimally via digital twinning.[14]
  - Polymers, e.g. biodegradable/compostable plastics in consumer products or packaging
  - Produce from controlled-environment agriculture.[15]
  - Surfactants via chemical synthesis, such as certain cosmetics, detergents, and emulsifiers

- Biomanufacturing—Adding value through the use of biological processes such as precision fermentation and genetic engineering

  - Alternative proteins via cell-culture[16]
  - Biofuels produced via fermentation or transesterification, e.g. bioethanol, biodiesel, renewable natural gas via anaerobic digestion, etc.
  - Crops with increased yields via genetic engineering.[17]
  - Industrial enzymes

- Ecosystem Services—Adding value through the use of ecological processes, either directly (services used in the economy) or indirectly (services that sustain other services and resources in the economy):

  - Air quality
  - Biodiversity
  - Carbon sequestration
  - Recreation/Wellness
  - Resilience (including diversity, redundancy, and panarchy/interconnectedness)
  - Water quality

Biomass,[18] and the farms and forests that supply it, are the foundation of these value chains. So too are ecosystem services, such as biodiversity, climate resilience, and water quality, among others. As such, the circularity and long-term health of the bioeconomy depend on ensuring that biomass and ecosystem services are sustainably managed and conserved.

The above taxonomy is not exhaustive; many other products fit within this framework. Readers may also note that this taxonomy does not include most food and feed production, which are probably the most commonly used biobased products in the world. Nor does it include pharmaceuticals such as vaccines and cell therapies, which are often produced via biomanufacturing. That is because these generally do

[14] reduces use of cropland, which is a non-renewable resource.

[15] reduces use of cropland, which is a non-renewable resource.

[16] reduces use of cropland, which is a non-renewable resource.

[17] reduces use of cropland, which is a non-renewable resource.

[18] Any material of biological origin that is available on a renewable or recurring basis, for example, plants, trees, algae, and waste material such as crop residue, wood waste, animal waste and byproducts, food waste, and yard waste | NIST Bioeconomy Lexicon.

not substitute renewable for non-renewable resources (though in some cases they do), which is the subjectively stated goal for this particular taxonomy. In any case, the goals of food security and public health very much stand on their own as drivers of public policy and investment.

3.4 Bioeconomy Engagement in the U.S. Government, 2010–2022

The use of the term "bioeconomy" in the U.S. Federal government dates to a 2010 Obama White House memorandum calling for increased research in biotechnology advances to address critical national needs[19] and a 2012 "National Bioeconomy Blueprint[20]" to develop strategic objectives to realize the full potential of the U.S. bioeconomy. This scope was broadened to place greater emphasis on the production and use of biofuels, bioproducts, and biopower with the release of a "Federal Activities Report on the Bioeconomy" by an interagency group co-chaired by the U.S. Department of Agriculture (USDA) and the U.S. Department of Energy (DOE).[21]

Federal engagement on bioeconomy increased during the first Trump Administration, following the release of an implementation framework "to increase government accountability and efficiency, maximize interagency coordination on bioeconomy research and other activities, and accelerate innovative and sustainable technologies that harness the nation's biomass resources,"[22] including establishment of the Defense Department's Bioindustrial Manufacturing and Design Ecosystem (BioMADE).[23]

In 2019, the Trump Administration hosted a White House summit to discuss key opportunities and challenges for U.S. leadership in the bioeconomy. In remarks at the summit, Michael Kratsios, Chief Technology Officer of the United States, stated the need to: (1) identify the most critical infrastructure in the bioeconomy and bottlenecks that impede our innovation or put our security at risk; (2) train future innovators and support our research institutions so that they have the resources and

[19] Peter R. Orszag and John P. Holdren, Memorandum: Science and Technology Priorities for the FY2012 Budget, Executive Office of the President, Office of Management and Budget, Washington, DC, July 21, 2010.

[20] White House, National Bioeconomy Blueprint, Washington, DC, April 2012.

[21] The Biomass Research and Development Board was established in P.L. 106-224 and reauthorized in subsequent Farm Bills "to coordinate programs within and among departments and agencies of the Federal Government for the purpose of promoting the use of bio-based industrial products."

[22] Biomass Research and Development Board, The Bioeconomy Initiative: Implementation Framework, U.S. Department of Agriculture, Washington, DC, March 5, 2019, p. vii.

[23] Department of Defense, "DOD Approves$87 Million for Newest Bioindustrial Manufacturing Innovation Institute," press release, October 20, 2020. To advance industry-wide standards, develop foundational technologies, foster resilient bioindustrial manufacturing, advance education and workforce development, and support essential supply chains.

protection they need to thrive; and (3) protect our genetic and biological data while safeguarding the freedom necessary for a robust and growing bioeconomy.[24]

At this time, the White House Office of Science and Technology Policy (OSTP) also issued a request for information on "notable gaps, vulnerabilities, and areas to promote and protect in the U.S. Bioeconomy."[25] The Trump Administration identified the bioeconomy as a key area of focus for federal R&D investments in both the FY2021 and FY2022 R&D budget priority memoranda.[26]

In 2020, the Trump Administration drafted a Bioeconomy EO to direct OSTP and the National Security Council to co-chair an interagency committee tasked with creating a national bioeconomy strategy within 210 days.[27] It was never issued, possibly due to the coronavirus pandemic, but it was likely the blueprint for the Bioeconomy EO issued in 2022[28] that gave the same direction to establish an Interagency Policy Committee led by OSTP and the White House National Security Council.

3.5 Bioeconomy Engagement in the U.S. Government, 2022–2024

Following the establishment of then-President Biden's Executive Order on Biotechnology and Biomanufacturing (EO 14081) in September 2022, emphasis broadened from its prior focus on biotechnology to increase emphasis on biomass production and biobased manufacturing. The "Bioeconomy EO," as it came to be known, served as the nation's bioeconomy strategy and assigned specific tasks and deliverables across the federal government.

The Bioeconomy EO elaborated upon more specific goals including climate resilience, food security and sustainability, and supply-chain resilience in energy and manufacturing. Whereas previous initiatives focused largely on biotechnology innovation and the capital-intensive research and development that drives it, the goals of the Bioeconomy EO necessitated an increased emphasis on biomass feedstock production and biobased product manufacturing and markets. This

[24] Office of Science and Technology Policy, Summary of the 2019 White House Summit on America's Bioeconomy, Washington, DC, October 7, 2019, p. 7.

[25] Office of Science and Technology Policy, "Request for Information on the Bioeconomy," Federal Register, vol. 84, no. 175, p. 47561, September 10, 2019.

[26] Russell T. Vought and Dr. Kelvin Droegemeir, Memorandum for the Heads of Executive Departments and Agencies, Subject: Fiscal Year 2021 and 2022, Exec. Office of the President, Washington, DC, August 30, 2019 and August 14, 2020.

[27] Nicholas Florko, "Abandoned Trump Order on the Bioeconomy Highlights a Path Forward for Biden—But with Mixed Reviews," STAT News, May 17, 2021.

[28] EO 14081: Executive Order on Advancing Biotechnology and Biomanufacturing Innovation for a Sustainable, Safe, and Secure American Bioeconomy (as of 1/21/2025 this EO remains in effect; not rescinded).

significantly broadened the bioeconomy's reach to include farms, forests, and enterprises of all shapes and sizes, and the many environmental and economic benefits they deliver.

Driven by appropriations of over $6 billion in federal bioeconomy investments from landmark climate and infrastructure legislation, a proactive whole-of-government structure was put in place to leverage the broad array of existing government programs and initiatives for rapid impact.

The Department of Agriculture implemented the largest part of this funding—$4.6 billion (described in further detail below)—through its work in biomass production and biobased manufacturing, given the Department's longstanding mandate to support the farming, forestry, and infrastructure that supply these value chains. Biomass production and biobased manufacturing were found to deliver high returns on publicly funded investments and de-risking, delivering greater impact at larger scales on shorter time frames, particularly in sectors with higher Technical Readiness Levels (TRLs), such as in biofuels, sustainable building materials, sustainable packaging, and non-woven textiles.

The Department of Defense announced over$1 billion in investment in domestic biomanufacturing to strengthen defense supply chains, accelerate the biomaterials development pipeline with the Air Force, Army, and Navy laboratories, and to establish a commercial investment program that seeks to industrialize maturing biomaterials.

The Department of Energy supported $264 million in projects through its Energy Earthshots™ Initiative, $151 million to scale promising technologies to convert biomass to low-carbon biofuels and bioproducts, $120 M to support research and field trials for biomass and waste feedstocks including CO2 gases, algae, and energy crops, and the development of microorganisms to make biofuels and bioproducts more affordable, and up to $200 million in cost-share to demonstrate an integrated hydrogen process to utilize captured carbon dioxide from ethylene production.

The Biden Administration established the White House National Bioeconomy Board (NBB) to coordinate the implementation of government-wide bioeconomy policies, including those outlined in EO 14081 and any future bioeconomy-related policy, and to serve as a forum for new federal policies to both promote and protect the bioeconomy at large. Reporting to the President, the NBB was comprised of one senior official from each federal Department acting on its Secretary's behalf. The Board was supported by a Secretariat, consisting of one or two senior staff members from each Department, which met bi-weekly to coordinate efforts, provide policy and technical guidance, and facilitate the development and practical implementation of interagency initiatives.

3.6 Bioeconomy EO Implementation at USDA: Biobased Value Chains

The cross-cutting nature of biomass feedstock production and biobased product manufacturing called for collaboration across the wide range of related programs and activities throughout the Department's Mission Areas, including research, policy, land management, data collection, financial support, and outreach. The Department established a USDA Bioeconomy Council at the Under-Secretary level (covering all the Department's diverse mission areas and agencies), which was staffed by a Bioeconomy Coordinating Committee (BCC) comprised of about 50 senior subject matter experts from across the Department. The Council and the BCC inventoried, tracked, and prioritized several dozen programs that contribute to the Bioeconomy EO's goals and identified policy changes needed to ensure their effectiveness.

The USDA Biomass Supply Plan and Implementation Framework ("Framework") provided a cohesive strategy for the US Government's bioeconomy enterprise in biomass production and biobased manufacturing, tracking and interconnecting dozens of programs and activities. This helped staff identify efficiencies and opportunities for collaboration across agencies and provided a menu for senior leadership to set priorities. The various activities were grouped into production, manufacturing, and markets:

1. Production and Supply of Biomass Feedstock
   (a) Improve utilization of residual woody biomass in materials and energy: Develop regional pilot(s) to expand woody biomass utilization in next-generation materials, and production of wood biochar for electricity and soil amendments
   (b) Enhance productivity and competitiveness of bioenergy commodities (corn, soy, sorghum, etc.): Improve tax credits and valuation methods for energy feedstocks; ensure accuracy and fairness of international biofuels markets and verification systems
   (c) Develop next-generation feedstocks[29] for emerging biobased-product value chains: Optimize incentives and insurance to increase adoption of intermediate oilseed crops; facilitate expanded cultivation and processing of strategic latex and lignocellulosic feedstocks.
2. Manufacturing Infrastructure for Biobased Products—Synergize infrastructure investments with emergent opportunities in feedstocks and markets:[30] Develop

[29] Including intermediate oilseeds (camelina, carinata, and pennycress) for biofuels, latex crops such as guayule and dandelion for domestic natural rubber, and lignocellulosic feedstocks such as wood processing residues and hemp for advanced building materials, composites, biochemicals, and soil amendments.

[30] Various financing programs administered by Rural Development and Forest Service including: REAP, 9003 Program, ABPP, HBIIP, B&I, REDL, TPEP, FPEP, Wood Innovations Grant programs, etc.

regional pilot(s) to establish or retrofit mill capacity near highest-priority wildfire zones to process non-sawlog wood material for advanced manufacturing and energy production; increase applications by bioenergy and biobased manufacturing stakeholders to USDA funding programs.
3. Market Development: Increase demand for U.S. biobased products by expanding Federal procurement and export markets, increasing BioPreferred® program participation, and improving measurement and classification systems.

3.7 USDA Programs Implementing Biobased Production under the Bioeconomy EO

The $3.1-billion Climate-Smart Commodities funded 135 projects to de-risk producers and enterprises adopting regenerative agricultural practices and supplying biobased value chains that substitute renewable for non-renewable resources in consumer and industrial goods.

USDA Forest Service's $190-million Wood Innovations Program made catalytic investments in the wood-based bioeconomy across 482 projects to support land management, wildfire risk reduction, and local economies. These projects supported the critical connection between healthy and resilient federal, state, tribal, and private forests and the wood products economy. Related programs also supported a 300% increase in biochar production, with over 600,000 green tons of biomass used to produce about 175,000 tons of biochar in 2023.

USDA's Rural Development mission area launched the $220 million Timber Production Expansion Program (TPEP), administered jointly with Forest Service, for loan guarantees to develop or redevelop wood processing facilities that will support fuels reduction on up to 20 million acres of the nation's highest-priority wildfire zones, and the $288 million Higher Blends Infrastructure Incentive Program (HBIIP) to increase availability and sales of domestic biofuels by more than 2.7 billion gallons annually. Additionally, USDA Rural Development's BioPreferred® catalog of biobased products added a total of 2835 new products and 1008 new companies—a 36% and 75% increase, respectively—since the issuance of the EO. At least 2359 companies and 10,715 products are now active in the BioPreferred® program.

USDA's Office of the Chief Economist (OCE) developed new protocols for climate-smart farming practices that would provide bio-refiners incentives for sourcing domestic feedstocks. For the "40B" Sustainable Aviation Fuels Credit, USDA developed a 40B USDA Climate-Smart Agriculture Pilot Program. OCE subsequently issued an interim final rule for "Technical Guidelines for Climate-Smart Biofuel Feedstocks." It established guidelines for quantifying, reporting, and verifying the greenhouse gas emissions with producing U.S. biofuel feedstocks. These guidelines may inform the subsequent development of requirements for other programs that incentivize low-carbon biofuels.

USDA's Agricultural Research Service and National Institute of Food and Agriculture invested over $500 million in biobased research and development, delivering advancements such as the first commercial harvests of new intermediate oilseed crops that provide fuel and feed sources without requiring additional cropland; compostable adhesives for price look-up (PLU) stickers, critical in maintaining foreign market access for US fruits and vegetables; bio-asphalts that generate fewer emissions; and biobased antioxidants for natural rubber in tires.

3.8 Lessons Learned About Bioeconomy Governance

- Bioeconomy can be all-encompassing; goals should reflect clear policy priorities. With definitions of bioeconomy often variable and occasionally vague, the Administration's clear expression of goals relating to climate, food security, and supply-chain resilience enabled implementers to set actionable priorities that went beyond virtue-signaling.
- Implementation of the Bioeconomy EO found that biobased value chains have a high degree of readiness to deliver strong returns on publicly funded bioeconomy investments. This was particularly the case in sectors at higher TRLs, such as in building materials, bioplastics, sustainable packaging, and textiles.
- Major de-risking and procurement initiatives drove a cohesive strategy along these lines, supported by collaboration across agency silos in forestry, agriculture, and research. Where the private sector was reluctant to take on the risk, historic public investments directly benefited forest enterprises, farmers, and small and medium manufacturing while improving land health, climate resilience, and carbon market opportunities.
- Clear direction and structure from the top. Agencies tend to be siloed contrary to the multidisciplinary needs of bioeconomy development. Presidential direction helped the sprawling Federal bureaucracy overcome these inherent barriers to collaboration.
- Leveraging existing programs fosters adoption and alignment in program delivery. By focusing on existing programs rather than inventing new ones, implementation relied on established protocols and relationships, and agency leaders could acknowledge credit for the work their teams already do. Otherwise, the complexity and novelty associated with bioeconomy might have deterred progress.

3.9 What Needs Improvement for Prioritizing Investments in De-risking the Bioeconomy

Government financing decisions commonly rely on scoring criteria related to generic factors like economic feasibility and operational readiness that apply to all sectors and geographies. Government efforts to go beyond these generalized approaches to prioritize sectors, segments, and geographies can be politically fraught and subject to abuse if not objectively supported. And even when credible analytical methods like Biomass Development Opportunity Zones are available with proven track records, agencies nevertheless struggle to align such methods with their regulatory protocols.

USDA's Biomass Supply Plan Implementation Framework avoided this pitfall in part by working the problem in reverse. The Department's existing programs were inventoried to consider how they cover a broad range of biobased sectors, from which Department leadership transparently selected areas of focus based on the Department's own operational experience and results. This provided a rational basis considering likelihood of outcomes based on USDA's own operations, but it did not allow for a systematic consideration of specific sectors, segments, geographies, or forecasted outcomes for ecological and socioeconomic resilience.

The Climate-Smart Commodities Program avoided this pitfall by developing and carefully vetting a series of criteria related to climate resilience, carbon market development, and benefits to farmers and smaller enterprises, especially those considered underserved; but considerations of sectors, segments, and geographies were also largely beyond reach for this program as well.

Most USDA Rural Development programs have general economic and feasibility criteria enshrined in legislation for their funding decisions. Specialized programs for individual sectors and geographies are sometimes specified in legislation (the so-called earmarks), but the use of objective methods for developing such legislation is rare.

Principles of circular value-chain analysis can support objectivity in identifying investment priorities across sectors, segments, and geographies, but they are not used in public investment decision-making for bioeconomy programs in the USA. This is likely due to lack of data and resources to adapt and apply such methodologies at national scales. The use of such methodologies in other national and multilateral bioeconomy initiatives, if any, may be hindered by the same problem.

3.10 Next Steps

As urgent demands on public sector funding increase, a higher standard of rigor in risk assessment and reduction will be required to attract private-sector investment. Methodologies based on principles of circular value-chain analysis can provide this rigor. Such methodologies should incorporate robust tools for forecasting changes

in ecosystem resilience, such as in well-established methodologies for growth-and-yield modeling in silviculture and forest stand dynamics, especially where advances in big data and AI can be leveraged to make forecasts with greater precision and confidence. For maximum effect, such efforts should dovetail with high-visibility development opportunities where public–private partnerships for investments in sustainability and innovation already have strong support.

Such methodologies should be adapted and synthesized based on comparative assessment of various action-oriented bioeconomy initiatives from around the world—particularly at the regional scale, where circular value-chain analysis may be more intrinsic or readily adaptable; in recent years, there has been a proliferation of regional bioeconomy initiatives covering a wide range of sectors, particularly (but not exclusively) in Europe, that would be well suited to such an assessment. Multidisciplinary graduate programs in bioeconomy should also utilize these frameworks to organize curricula and prioritize research, and to assemble cooperative extension programs that integrate these methods in bioeconomy development practice.

Government financing decisions commonly rely on scoring criteria related to generic factors like economic feasibility and operational readiness that apply to all sectors and geographies.

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Chapter 4
Building Supply Chains to Create a Climate-Smart Circular Bioeconomy

David Zilberman, Jonathan Tillinghast, and Sadie Shoemaker

4.1 Introduction

The twenty-first century challenges us to alter how we produce energy and materials to drastically reduce greenhouse gases and pollution, protect biodiversity, and provide new creative employment opportunities. The circular bioeconomy is a significant avenue to address these challenges. Building it requires creating multiple supply chains for new feedstock and processing these feedstocks to produce multiple products that are then distributed and utilized. The notion of Climate-Smart Circular Bioeconomy (CSB) integrates several major approaches to address climate change, sustainability, and rural development. Each of these terms has multiple interpretations, and we will present ours here. Climate-Smart agriculture has been a compromise between the desire of developed countries to modify resource management to mitigate climate change and the needs of developed countries to adapt and grow, so Climate-Smart agriculture emphasizes technologies that address climate change challenges and lead to economic growth (Lipper et al., 2017). The bioeconomy consists of sectors of the economy that use natural resources with advanced scientific knowledge to produce multiple goods and services, including food, fuel, chemicals and pharmaceuticals, sequestration, and other environmental activities (Wesseler & von Braun, 2017). Different countries have their own bioeconomy plans. For example, the U.S. bioeconomy policy emphasized biomanufacturing, biofuel, and recycling, and relies heavily on modern biotechnology as is reflected by

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the NSF agenda.[1] Latin America emphasizes the use of biotech and biofuels.[2] The EU emphasizes support for the bioeconomy across multiple sectors—agriculture, forestry, and fisheries—and downplays the role of biotechnology.[3] There is a growing research agenda to grow a circular bioeconomy that will address resource degradation in Africa and climate change (Feleke et al., 2021). The notion of circularity emerged from the realization that while many production systems use inputs to produce outputs, they also produce residues that are sources of environmental degradation. With circular systems, there is an emphasis on reuse, recycling, and reduction of the residue and an aspiration to eliminate residues (Fullerton et al., 2022).

The transformation to the bioeconomy is a work in progress. While renewable technologies like solar and wind have a potent impact, more is needed to transition from a non-renewable to a renewable economy. The bioeconomy will augment the capacity for a transition to a renewable economy. The growing capabilities of natural sciences, information and data sciences, and transportation systems increase the ability to develop a CSB. The bioeconomy consists of several integrated activities that build innovation and product supply chains, starting with the research lab and ending with consumers. But, the system is circular as we aim to recycle and reuse residue products. The construction of the bioeconomy will consist of introducing innovations by developing new products and services. Innovation supply chains are the activities that lead to implementable innovations (discovery, development, upscaling). The integrated activities that result in new products are product supply chains. Production activities may result in residues that may be untreated waste and cause environmental side effects. Still, these residues will be used as input to produce valuable products in a circular system. Therefore, in this chapter, we will analyze the main components of a CSB through supply chains. The first section of this chapter will further introduce different kinds of supply chains, distinguishing between innovation and product supply chains, emphasizing the symbiotic relationships among supply chains, and the factors affecting their industrial structure. It will be followed by identifying different types of bioeconomy supply chains, including blue, green, brown, and white, having to do with bodies of water, flora and fauna, waste products, and biomanufacturing, respectively, and the challenges that the development of each kind of supply chain faces. We will identify issues of risk and resilience, credit, and the role of policy, which will lead us to the conclusion.

[1] https://www.casa-bio.net

[2] https://academic.oup.com/aob/advance-article/doi/10.1093/aob/mcae191/7848661#:~:text=LATAM%20plays%20a%20significant%20role,FAOSTAT%2C%20Biotec%2DLATAM

[3] https://research-and-innovation.ec.europa.eu/research-area/environment/bioeconomy_en

4.2 Symbiotic Supply Chains

Supply chains are a sequence of activities associated with producing a good. These activities produce economic value, and some distinguish it from the value chain, which traces the evolution of value within the operational supply chain (Holweg & Helo, 2014). We will apply a broad perspective on the supply chain and interpret it to include the activities and institutional structure that conducts them to create value. We will distinguish between two categories of supply chain: the innovation supply chain, which produces new implementable concepts, and the product supply chain, which implements them. The relationship between the two is symbiotic, with each supply chain deriving value from the other. Lessons from the product supply chain affect the behavior of the innovation supply chain, and the innovation supply chain begets new product supply chains.

Supply chains may include many segments. As is common in the literature, we assume they include three elements: upstream, midstream, and downstream (Macchiavello et al., 2022). Of course, in a circular economy, there are innovation and product supply chains for circular activities. In the case of the innovation supply chain, the upstream will be research, the midstream development, and the downstream scale-up. The product supply chain includes feedstocks, processing, and distribution. In the case of an agricultural industry producing biofuels, the feedstock may be sugarcane (*upstream*), a refinery producing ethanol and biogas made from the sugarcane (*midstream*), and then pipelines and gas stations (*downstream*). Empirical analysis may further break down these supply chains: the feedstock has its own innovation and product supply chains. The distribution of products may include shipping, wholesale, and retail, and it depends on the vehicle supply chain. The economy consists of multiple linked supply chains. They may be symbiotic because they coevolve. Feedback from the product supply chain may lead to new innovations. Changes in distribution (establishment of supermarkets) may affect production and processing, for example, by requiring higher standards and different products (Barrett et al., 2022).

One of the characteristics of a modern economy is the high rate of innovative activities that may result in new products. Innovation and product supply chains have multiple organizational structures. Innovation may result in a final product as well as multiple intermediary products. For example, introducing a new fruit type requires genetic material, specialized harvesting equipment, etc. The individuals or firms that establish a new product supply chain may establish its structure based on economic considerations (Coase, 2012). The industries that produce a new product may have different structures. For example, the feedstock for bioethanol in the United States is corn produced by multiple farmers, refined mostly by small refiners, and sold to oil companies. In Brazil, there are situations of vertical integration where oil companies own sugarcane plantations and refineries and sell the biofuel to their final consumers.

Below, we present different institutional structures of innovation and product supply chains, and their implications. Here we contribute to the existing literature

circularity considerations, analyzes the design of supply chains when their residue products (which may produce externalities) are considered, and discusses where technologies are introduced to recycle and reuse these wastes.

4.2.1 Innovation Supply Chain

The innovation supply chain (ISP) includes an upstream, which is the creation of an idea; a midstream, which is the development of this idea; and a downstream, which is the upscaling and commercialization of commercial product service. There are different types of innovation supply chains. One category that is very popular in the modern era is the educational-industrial complex, where innovation starts with a scientific discovery that is further developed and then commercialized, eventually leading to a commercial product transferred to a product supply chain. For example, the recent mRNA vaccine is an outcome of the educational-industrial complex. The discovery was made by two academics—Katalin Karikó and Drew Weissman—who won the Nobel Prize in 2023 (Krammer & Palese, 2024). The startup BioNTech[4] developed the vaccine and later partnered with Pfizer, which commercialized the product. There is a growing recognition of the importance of universities as centers of innovation and the offices of technology transfer linking university research to the private sector (Zilberman et al., 2022). There is very substantial evidence of the impact of this kind of institution (Siegel & Wright, 2015).

A second innovation supply chain category is the generation of recombinant innovation. Upstream of this ISP, an entrepreneur comes up with an idea for a product and may approach an innovation firm or build a research unit that will take advantage of existing technologies and develop innovations. Edison was an entrepreneur with an innovation firm producing multiple innovative products. Edison's lightbulb and Ford's assembly line were recombinant innovations adapting technologies from other sectors to produce cars (Hargadon, 2003). A third category is relentless innovation, where a company that controls a technology continues to improve the technology in its labs. This is where symbiotic relationships exist between a product supply chain, which may report on problems with an existing product or technology, and the innovation supply chain, which develops an improvement (Phillips, 2012). The fourth form is government innovation, where government agencies have an idea and utilize their resources to pursue it. Water projects are examples where government officials and politicians influencing interest groups decided to build a canal transferring water from one region to another. The government agency designed the canal and then paid to develop it. This is the story of some of the water projects in California (Zilberman, 2023).

Every country may have its own innovation supply chains. A region with strong universities and entrepreneurial capabilities, like Silicon Valley, is more likely to

[4] https://www.biontech.com/int/en/home.html

have a potent education-industrial complex. Regions with strong manufacturing may produce recombinant innovation—this is the case with traditional Chinese medicine (Wu et al., 2024). Major corporations—for example, tractor companies—emphasize relentless innovation, introducing new models and improved products. In most regions, government innovations result in new infrastructure and other common facilities.

4.2.2 Product Supply Chain

Many existing product supply chains are analyzed as linear. The upstream includes the producers of feedstocks, the midstream processing and distribution, and the downstream consumer. However, the reality is that production systems produce residues, which may have negative side effects, but they can also be used as feedstock for new products (Khanna et al., 2025). Thus, in Fig. 4.1, we consider a straightforward expansion of our approach regarding the element of circularity. We have the innovation supply chain that leads to a product supply chain, and through feedbacks, the two systems coevolve. The product supply chain has several elements, and each element produces a residue; there is a residue from the production of feedstock, processing the feedstock to produce a product, transporting the product to the consumer, and consumption. The residue at each stage then may be converted by a circular supply chain to new final products, and there will be some unused residue that hopefully will decline over time as new circularity activities are discovered.

We envision a network of multiple supply chains of both innovations and products. Each product supply chain results in residues. For each residue, there may be both the innovation and product supply chain that will produce new products. These two processes of innovation and circularity are continuing, allowing for a sustainable economy that relies on renewable products.

In the case of food, the feedstock may be rice, and the residue may be greenhouse gas emissions and chemical runoff from fertilizer. Precision agricultural practices, cover crops, and converting the rice fields into wetlands, among others, may help reduce residues. In the midstream, the rice may be packed and converted into multiple rice products (Natuhara, 2013). Again, this process may generate greenhouse gasses and multiple by-products. Consumers may not eat all the food: some may be thrown away, resulting in methane emissions and other damaging products, but they may also be reused to produce alternative proteins or fed to chickens. Our framework is static for simplicity, but the challenge of circularity is the dynamic dimension. Variable inputs generate temporal externalities when produced or consumed, but capital goods generate end-of-life externalities.

We expand upon a simple framework by Zilberman et al. (2023a) to analyze supply chains. This framework does not explicitly include environmental issues, but after we present some of its basic points, our circularity considerations affect its outcomes in terms of prices and quantities. The circularity considerations will be

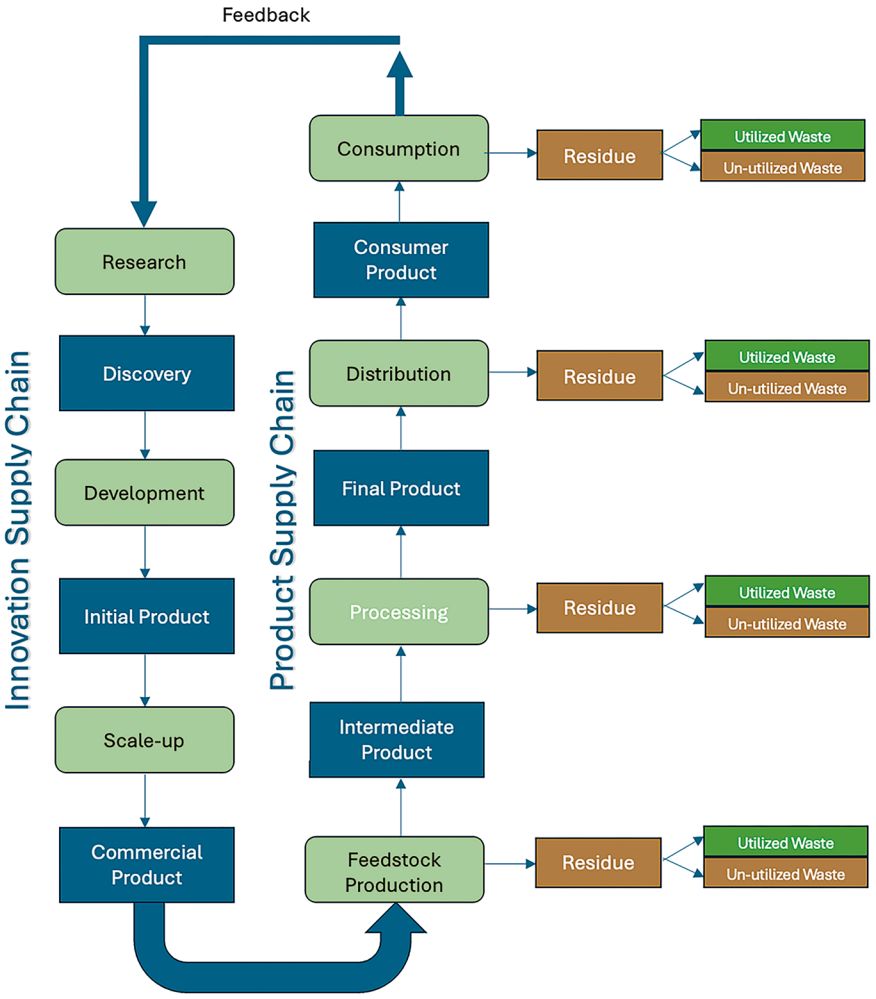

Fig. 4.1 Circular innovation and product supply chains

largely affected by government policy, particularly the extent to which governments tax pollution, subsidize the adoption of clean technologies, or adopt regulations that impose green activities.

We will start without explicitly considering the externalities. We assume the entrepreneurs who control innovation design and implement their product supply chains. These supply chains evolve based on economic performance and changes in technology and regulations. The first stage in the design of the supply chain is assessing demand based on surveys and other assessments and considering that demand may be affected by the choice of marketing strategies. Demand assessment is constantly changing based on learning from experience. A supply chain has

multiple components, and an entrepreneur must determine the initial structure. Consider a case, a three-stage supply chain with a production of feedstock upstream, processing and distributing midstream, and consumers downstream. It is reasonable to assume that the entrepreneur who establishes a supply chain is more likely to control the processing and midstream activities. They must determine to what extent they should engage in feedstock production or retailing. Establishing each element of the supply chain requires investment and human capital.

The objective function of the entrepreneur is to maximize the net present of expected profit, subject to credit and resource availability. Following Zilberman et al. (2023a), the entrepreneur's profit in each period includes revenue from selling the product to the retailer minus the cost of processing and feedstock and the cost of capital. The entrepreneur may buy all of it if they do not have any relative advantage in growing the feedstock. They may produce it themselves if there are no other effective producers. They may produce only part of the feedstock such that their cost of production of an incremental unit is equal to the expenditure of buying an incremental unit. The quantity of output produced is at the level where the incremental revenue for additional units equals incremental cost.

Our analysis indicates that if, over time, the cost of producing feedstock by outside suppliers declines faster than the cost of producing them in-house, the share of input purchases increases. This was the case, for example, when European companies started to grow flowers in Africa to sell them in Europe. Initially, there were no African growers, and the exporters needed to grow the flowers themselves. Over time, the African farmers learned how to grow the flowers cheaply, and the processers/shippers concentrated on processing.

The prices and quantities of products, as well as the structure of the supply chain, may change over time. If the demand for output increases and the marginal cost declines because of learning, then overall output increases. If the entrepreneur has market power compared to external feedstock suppliers, it will pay them below the marginal cost of feedstock production and make monopsonistic profits. If the processor's scale is relatively small compared to other firms producing close substitutes, then the entrepreneur has minimal control of the output price. In the case of biofuel, which is a substitute for gasoline, the price is dictated, to a large extent, by the price of gasoline. However, there may be situations in which entrepreneurs have significant market power (e.g., when the entrepreneur is the only producer of a valuable enzyme or biopharmaceutical, and they can impose monopoly prices).

Besides short-term decisions, the entrepreneur also makes long-term decisions. The amount invested in each period is at the level where the cost of one capital unit equals the expected net present value of the marginal benefit of capital over time. So, a biofuel refinery determines how much to expand. In that case, the expected discounted net present value for the extra amount of biofuel and other products produced must be equal, at the margin, to the cost of capital. Note, however, that the availability of capital constrains entrepreneurs who start supply chains, which may affect the supply chain's design and structure. Some of the producers of pre-cut lettuce started as large lettuce growers but sold their lettuce farms to invest in processing (Zilberman et al., 2023b). Tyson is a primary meat processor. They elect to sell

chicks and feed to chicken farmers who raise and process broiler chickens. Tyson buys and processes these chickens. They do not want to raise the chickens because they want to avoid the significant investment in real estate and use their financial resources to expand their activities in other meat processing. Tyson gains some monopsony profit from this arrangement but can keep it because of the economics of scale (Schwartz, 1991). There is a need for improved circular solutions for poultry waste that can be the result of improved technology induced by policy.

A key element of supply chain design and activities is the feasibility of moving resources over space cheaply and safely. Nelson (2022) suggests that the roads the Romans built and the security they provided led to grain trades throughout Southern Europe and the Middle East, resulting in long supply chains for other products. The destruction of infrastructure and overall lack of security after the fall of the Roman Empire led to the emergence of an autarkic system with local supply chains. One feature of the modern era is the reduced cost and increased transport safety, leading to long, globalized systems. Innovation supply chains started by governments, which developed new means of transportation, from canals to railroads and highways, have enabled the development of multiple-product supply chains and expanded trade. Furthermore, introducing multiple types of chemicals and other treatments to reduce pest damage and weather-controlled systems for trucks, trains, boats, and shipping through airplanes enabled long supply chains and global trade. Increased global mistrust between countries (the USA and China) and awareness of the vulnerability of supply chains to random shocks (pandemics or tsunamis) led to an increased emphasis on resilience, leading to shorter and controllable supply chains with more redundancy.

The notion of food security must incorporate concerns about food supply and the ability to transport supply and overcome both logistical and political barriers. Concern about climate change and climate shocks may lead processors and retailers downstream to contract multiple upstream sources for feedstocks (Reardon & Zilberman, 2018). The design of our circular supply chain must be modified to consider logistic and policy constraints, as well as climatic and environmental considerations.

The example of organic farming illustrates the impact of environmental concerns and profitability on supply chains. It does not necessarily improve the environment but is perceived as a green practice and a source of premium. There is a growing emphasis on developing supply chains for products that follow practices perceived to be virtuous, such as fair-trade coffees (De Pelsmacker et al., 2005). The true environmental impact of these supply chains must be evaluated, and they may need to be modified to reduce negative environmental side effects and improve pollution. Ronald and Adamchak (2018) suggest that enhancing organic farming with modern biotechnology would eliminate the use of chemical pesticides and increase the efficiency of organic farming, enabling it to be more circular.

Khanna et al. (2025) suggest that linear practices have prevailed because the cost of pollution has been minimal for many years. When James Watt invented the steam engine, or when oil started being used for transportation, no one worried about air pollution, and by default, the right to pollute was established. Only after awareness

of the damages of pollution arose did policymakers establish regulations to control it. That is true with air pollution, water pollution, and climate change.

Adopting circular practices may require strict regulation and enforcement of environmental laws against pollution and investment in R&D, resulting in supply chains that rely on residues as inputs for new products, which we will discuss in more detail later. Now, consider a situation where production residue—greenhouse gases, dry wood that can be burned, contaminated water, and food waste, for example—are taxed or regulated so that the firm that generates these residues pays for each unit of residue. Already, the farmer must pay refuse fees for disposing of waste. Still, if the fees become higher, they may think about alternative solutions, using the residue as inputs to produce valuable products. For example, wood can be converted to biochar and rejected food products may be used to feed black soldier flies, which are used to produce protein (Wang & Shelomi, 2017; Sheppard et al., 2002). Thus, the combination of availability of technology that produces economically viable circular products, a high fee for residues, and a sufficient price for circular products will lead to the introduction of circular activities. Suppose a producer of a primary product chooses between paying a fee for residue or using the residue to produce a circular product. Since the amount of residue increases with the production of the primary product, introducing a feedstock penalty when there is no alternative will reduce the quantity of primary product produced. On the other hand, if the residue is the input for a valuable product, then increased primary products may become profitable. So, introducing the circular economy may increase the primary economy, while a penalty on residues in the primary economy will reduce its size.

Introducing regulations and technologies that establish the circular economy will modify existing supply chains by changing how residues are treated and developing new supply chains in industries that rely on residues. These industries will be key components of the bioeconomy.

4.3 Supply Chains in the Circular Bioeconomy

Establishing the circular bioeconomy is a big challenge, but we do not have to start from scratch. The bioeconomy has been a dominant part of the economy for a long time. Horses and other animals were major means of transportation and power before cars and engines. Fermentation and other processing allowed us to preserve food and produce bread, cheese, and alcohol (a medicine throughout history). Long supply chains have enabled trade in grain, spices, tea, and other valuable products. The discovery of fossil fuels provided alternative energy sources and reduced the relative importance of the traditional bioeconomy. However, reliance on non-renewable resources is not sustainable, especially given the environmental impact of the fuels predominantly used globally. So, we must turn to the bioeconomy to replace non-renewable resources. While the flaws of modern food systems—in terms of food safety, quality, and security (Marucheck et al., 2011)—are exposed constantly, we recognize that they reduce the share of food budgets below 50%, and

only a small share of the labor force in the developed world is employed in agriculture (Rausser et al., 2015). The immense infrastructure for storing, processing, and transporting food and lumber products and the associated institutions for trading and finance worldwide provide a foundation for producing energy, minerals, and materials in the CSB. The modern bioeconomy will also benefit from new life and information science capabilities that will accelerate the production of new supply chains, making the bioeconomy nimbler and more resilient.

It is helpful to distinguish between several critical segments of the bioeconomy. The blue bioeconomy utilizes creatures of the bodies of water—fish, algae, and other aquatic species—as feedstock. They are used to provide food, serve a significant role in carbon sequestration, and provide energy and fine chemicals. The blue bioeconomy contains traditional fisheries producing fish and seafood, as well as the modern production of algae. It includes both production in sea and lakes, as well as aquaculture systems. Relatively little is known about algae and other components of the blue bioeconomy. We also must distinguish between microalgae and macroalgae. Microalgae already produce fine chemicals such as beta carotene and spirulina, food colorings, and many active biomaterials (Hachicha et al., 2022). Macroalgae consists of seaweed that lacks lignin and grows much faster than sugarcane (Mohapatra et al., 2019). Research on the blue bioeconomy must emphasize its potential as a source of food, chemicals, and carbon sequestration, and emphasize a need for protection against depletion of fish stocks and protection of the marine environment.

The green bioeconomy relies on terrestrial flora and fauna. Plants are the main food source, feeding of humans and other animals. To expand the bioeconomy to produce other materials beyond food, we have to increase the productivity of agriculture. Livestock is a major source of protein, and livestock production produces many other products, including leather and inputs for medicine. However, plants and livestock systems produce significant amounts of residue that must be utilized. Modern biotechnologies and other science-based approaches can increase yields, and the input-use efficiency of animal and plant production can reduce the footprint of food production. The footprint of food production can also be reduced by increasing the efficiency of conversion of plants to meat. Technologies that increase the precision of application input, monitor the movement of residue, and protect sensitive areas from chemical damage will be important to develop a more sustainable green bioeconomy. The green bioeconomy is also a source of lumber and wood. Increasing the productivity and capacity to utilize wooden materials for long-term activities (e.g., construction) is a significant challenge that may require extra investment in research and training. Trees and plants can also be used for sequestering carbon and as a food source. Since a major contributor to the greenhouse gas emissions from biofuels is the use of fertilizer, developing technologies of nitrogen fixation or use of renewable energy to produce nitrogen can reduce the nitrogen emission of biofuels. Similarly, constructing housing from wood can allow sequestration and save the large amount of greenhouse gasses associated with producing concrete and other materials.

The microbial bioeconomy contains multiple microbial organisms that can assist in energy recovery, waste management, food and chemical production, recycling, and medicine. The brown bioeconomy uses residue products as feedstock. Each has its specific challenges and requires its supply chain and treatment. Designing supply chains for waste management requires low-cost and convenient collection, transport, and processing solutions. In each case, we need to assess potential across locations over time. The gains from waste management can be substantial, but some benefits are public goods. Namely, they provide non-excludable benefits to many individuals. Other benefits are still being determined. Removing dry wood from forests reduces the risk of forest fire, greenhouse emissions, and destruction of life and property. Developing products, such as biochar that can use wood residues will improve the economic case for their performance.

The white bioeconomy consists of biomanufacturing in labs, greenhouses, and factories. It may result in the bioengineering of new organisms or products. Bioengineering is a growing field that results in various medical applications [stem cells, tissue engineering (Khademhosseini et al., 2006)], chemical applications (Kumar et al., 2007), neurological applications (Stark, 2012), and others. The educational-industrial complex has already played a major role in developing biomanufacturing innovations taking advantage of advanced biotechnology methods that resulted in products like artificial insulin, the COVID-19 vaccine, and many other medical treatments that are behind the success of companies like Genentech, BioNTech, and Moderna. The brown bioeconomy is reusing and recycling materials that might have been contaminated and defective as feedstock to produce other materials, including food for humans. Thus, developing the brown bioeconomy requires introducing technologies for monitoring, sorting, verification, and protection strategies in transforming residue into valuable products. Waste products and residues include both unutilized outputs (food waste) and unutilized inputs that may contaminate the environment. Therefore, waste management and enhanced circularity should require the introduction of precision technologies that optimize input use to different environmental conditions and thus increase yield and reduce residue. It requires monitoring and controlling the movement of residues to prevent ecological damage. It may require the use of life cycle analysis to quantify the outcome of a system over space and time and the introduction of end-of-life procedures to prevent damages. The use of life cycle analysis requires having databases that will recognize the heterogeneity and allow flexibility in designing new systems and the development of digital twins (digital replicas of physical products) that will allow the simulation of the impact of changes in systems virtually before they are introduced (Mengi et al., 2024).

The residue supply chain should be developed gradually as research would increase the safety of different products and consumer confidence in such products. One example is the reuse of treated wastewater for irrigation and drinking. In addition to funding procedures that would assure the safety of this water, consumer acceptance is a problem, but attitudes are improving over time with exposure and education (Verhoest et al., 2022).

The definitions of different categories of bioeconomy are not exclusive, and there are linkages between the various types of bioeconomy. With circularity, the green, blue, or white bioeconomies may result in waste materials that will be processed in the brown bioeconomy and then reused in the green bioeconomy. For example, animal waste can be a feedstock in the brown economy to produce fertilizer for the green bioeconomy. The bioeconomy can play an important role in carbon sequestration and storage. Trees and plants sequester carbon. Biochar allows for storing the carbon from residues that otherwise might generate greenhouse gas emissions by decomposition or fire. It is useful to expand the notion of the bioeconomy to "biochem-economy," which includes multiple solutions that may rely both on biological and chemical solutions to the sequestration and storage challenge of climate change.

Each bioeconomy consists of multiple synergetic supply chains for innovations and products. The structure of various supply chain stages varies between products and locations. Agricultural commodities tend to be produced in competitive industries, but the distribution of those commodities tends to be concentrated. The supply chain of many food products is shaped like a champagne glass, based on many farmers, a narrow middle of processors, and a wide consumption of retailers and consumers. There is high concentration and monopoly power in the pharmaceutical and medical industries, where companies take advantage of the economies of scale and production and rely on exclusivity associated with patents (even though companies may sell rights to use the patent to others). At the same time, multiple startups have developed new technologies. Some became major companies, while others are taken over by the majors or disappear (Graff et al., 2020).

A supply chain is as strong as its weakest link, and supply chain management must recognize the mutual dependence of different segments. A supply chain's resilience reflects its ability to overcome a barrier to the flow of products throughout the chain. Thus, improved infrastructure that allows movement within the supply chain and increased redundancy tend to increase resiliency. The capacity to innovate and modify the supply chain is another resilience indicator. The avian flu pandemic of 2019–2021 illustrated how vital supply chains could adjust to binding constraints. For example, consumers' reluctance to go to stores and restaurants led the supply chain to pivot to increased digitization in the food sector and the emergence of a much stronger food delivery sector (Reardon et al., 2021). The ability to pivot and overcome obstacles is vital in circular systems that aim to minimize pollution while providing output. Livestock facilities that generate waste products need to address the environmental damages associated with overflow of waste containment facilities in cases of flooding (Wing et al., 2002). With climate change and the increased likelihood of storms and extreme events, resilience to shocks is crucial. In many cases, circular systems should consider relocating away from vulnerable areas to enhance their resiliency.

4.4 Policy Implications

The development of CSB is important for addressing climate change and other environmental problems and can be a source for rural development and economic growth. However, several policy initiatives are required to help develop and implement innovations that result in viable supply chains. The development of CSB is constrained by climate change denial that, in most cases, reflects self-interest and comes along with heavy constraints on biotechnology. Incentives to develop climate-smart strategies are more likely to emerge once climate change acceptance is broader. The lack of acceptance of agricultural biotechnology has resulted in its low adoption rates in some parts of the world (United States, Brazil, Argentina). Many developing countries that could mostly benefit from the technologies have not adopted them because of political pressure. A major regulatory factor impacting the utilization of CRISPR, GMOs, and other biotechnologies is the potential to accelerate the introduction of new varieties, increase yield, and reduce pollution (Zilberman et al., 2018). It will be important to establish an international commitment to establish science-based policies and regulations based on risk–benefit analysis, which will enable the use of biotechnology to address the challenges of climate change and pollution more broadly.

Because climate change is a global problem, research, development, and outreach are important to develop local solutions worldwide. It will not be controlled if developing countries cannot address climate change and contribute to its mitigation. Thus, there is a need for much greater global investment in solving the agriculture and resource challenges of the developing world, which includes extension and support for implementing innovations that will lead to the establishment of local circular bioeconomies. The same technologies may have different supply chains in different countries. For example, the use of algae as a source of food and chemicals can be done in a capital-intensive way in developed countries and a labor-intensive way in developing countries. There is a need for scientific research and technology transfer to establish these technologies. One emerging avenue to expand the bioeconomy in developing countries is increasing the responsibility of the Consulting Group on International Agricultural Research (CGIAR).[5] Indeed, the portfolio of the CGIAR in 2025 includes "tackling climate change, food security, and biodiversity loss through global partnership and transformative solutions.[6]" It will be useful if the CGIAR permanently sees its role as a vehicle to expand the bioeconomy in developing countries. It can be the foundation for an industrial complex in the developing world, expanding its activities to include extension and help form startups. The scientists of the CGIAR and the universities in developing countries should not be prevented from contributing to establishing new enterprises and being part of it. But this big agenda requires much larger support. The budget of a more ambitious

[5] https://www.cgiar.org

[6] https://www.cgiar.org/news-events/news/cgiars-new-portfolio-responds-to-the-challenges-of-our-time/

CGIAR should be twice as much as its current level and maybe even more. But, at the same time, it would be evaluated by its ability to contribute to the emergence of circular bioeconomy sectors.

The establishment of CSB will require incentives and interventions. Ideally, we will see the emergence of polluter-pays policies like carbon pricing and pollution taxation. Regulations like the low-carbon fuel standards in California, which set an upper bound on greenhouse gas emissions from fuels, can be quite effective. Subsidies for research and development and for establishing new green industries can also be an important policy. Evaluating existing regulations, their impact on greenhouse gasses, and the ability to innovate will be valuable. An example is zoning. Setting strict limits on housing densities in major cities may lead to large concentrations of populations in suburbs and large volumes of greenhouse gas emissions from commuting. One major scientific challenge is to develop a carbon accounting system so each firm's and individual's emission and sequestration will be registered, facilitating more effective development of carbon pricing or regulation. With reliable accounting across all carbon-related activities, society can develop systems of carbon credit where individual behavior automatically will be accounted for, and transaction costs will be reduced. With this system, the adoption of carbon-saving innovations will provide credit that will be compensated by carbon pricing systems.

The development of supply chains in the bioeconomy will require research investment, standards establishment, and infrastructure development. We do not yet have sufficient research on the workings of supply chains and the interactions within supply chains and between different supply chains. Even less is known about the design and workings of circular supply chains. Establishing circular supply chains requires both new innovative efforts to develop new technologies to utilize residues and product supply chains to conduct circular activities using residues as feedstocks. Research should identify new biomass sources and the potential products they may produce. Particular emphasis should be given to identifying the products that can be produced from residue and the mechanisms to do so. Research is needed to improve procedures for producing intermediate feedstocks economically and resiliently. Research efforts at different stages of the supply chain, from the genetics of feedstocks to processing to transportation and distribution, should be coordinated to take advantage of synergies and reduce costs.

In addition, governments, domestically and internationally, should establish standards for communication and regulation of the performance of different aspects of the supply chain. Science-based regulation should be provided promptly, and low-cost monitoring and certification systems should be created, which will reduce the cost of investment in supply chains and the uncertainty associated with it, contributing to the growth of the bioeconomy. The development of supply chains will benefit from investment in infrastructure and training. This will enhance the ability to access high-cost research facilities, specialized equipment, and the trained workforce needed to develop a new sector.

One obstacle to developing circular supply chains is the chicken and egg problem. The development of new bioproducts requires investment in feedstock, processing facilities, and equipment to use the by-products. For example, the production

of a new biofuel requires investment in feedstock, biorefineries, and equipment (cars, trucks) to use it. Farmers will not grow a new feedstock unless there is a buyer, and a refinery might not be established unless there is a feedstock and a buyer of the final product. To induce adoption, if the net social benefit of the product are benefits, the government should interfere. The government may provide insurance to feedstock producers and may need to purchase some of the products from processing to accelerate the emergence of the industry. Solar energy and electric cars emphasize the importance of government investment, subsidies, and provision of markets needed to support the establishment of supply chains for new products.

Finally, the establishment of the bioeconomy will depend on public and private provision of funding for both the innovation and product R&D of the bioeconomy. Public sector funding of research and early development activities, availability of both public and private finance to startups that develop and scale up the technology, and a credit system that enables the commercialization of the innovation are essential for the development of a CSB.

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Chapter 5
Bioeconomy, Agriculture, and the Circular Economy: Opportunity and Challenges. Lessons Learned from the EU BioMonitor Project

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5.1 Introduction

The global pursuit of a more sustainable development has brought the bioeconomy concept to the forefront of policy discussions, research, and industrial innovation (M'barek & Wesseler, 2023). The bioeconomy offers a transformative pathway that utilizes biological resources to drive economic growth, environmental

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sustainability, and social well-being. This chapter explores the evolving landscape of the bioeconomy, particularly focusing on its intersection with agriculture and the circular economy, drawing insights from the BioMonitor project.

The bioeconomy encompasses a diverse range of sectors and systems that rely on renewable biological resources, including agriculture, forestry, fisheries, as well as all kinds of industries processing biomass (Kardung et al., 2021). One crucial goal is to replace fossil-based inputs with bio-based alternatives to reduce greenhouse gas emissions while fostering innovation and economic resilience. The European Commission defines the bioeconomy as incorporating all economic and industrial sectors that produce food, feed, bio-based products, energy, and services from biological resources (European Commission, 2018). This broad definition highlights the bioeconomy's potential to contribute to multiple Sustainable Development Goals (SDGs), including food security, climate action, and sustainable consumption.

However, the bioeconomy's interpretation and implementation can differ across countries and institutions, influenced by local priorities, resource availability, and policy frameworks (M'barek & Wesseler, 2023). The European Union has promoted the bioeconomy through initiatives like the updated Bioeconomy Strategy and the Horizon 2020 BioMonitor project. The latter has developed new methodologies and indicators to measure the bioeconomy's size, growth, and sustainability impacts, addressing critical gaps in data and knowledge.

A central theme in this chapter is the integration of the bioeconomy with the circular economy, a concept that emphasizes continual material use, resource efficiency, and waste minimization. The idea of a circular bioeconomy merges these two paradigms, promoting the sustainable use and reuse of biological resources. This synergy is essential for achieving long-term sustainability goals, aligning economic development with ecological boundaries (Kardung et al., 2021).

This chapter also revisits historical economic theories, such as those proposed by the Physiocrats and von Thünen, to contextualize the principles of the circular economy within a broader economic framework. It underscores the relevance of price systems, spatial logistics, and resource flows in shaping sustainable economic systems. Furthermore, this chapter presents empirical findings and methodological

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innovations from the BioMonitor project that enhance our understanding of the bioeconomy's contributions to sustainable development. It explores advanced modeling tools such as input–output analysis, material flow models, and hybrid frameworks, which provide valuable insights into the bioeconomy's economic, environmental, and social dimensions. Finally, this chapter concludes with future opportunities and challenges that await the EU bioeconomy.

5.2 Bioeconomy and Sustainable Development

Over the past decades, significant advances in life science and biotechnology and a shift in public attitudes have led policymakers to increasingly prioritize the bioeconomy as a key strategy for addressing global challenges such as food security, healthcare, resource constraints, environmental preservation, and climate change (Wesseler & von Braun, 2017; Zilberman et al., 2018). To promote the development of bioeconomy, the US released a *National Bioeconomy Blueprint* in 2012 (The White House, 2012). Similarly, the European Union (European Commission, 2018; European Commission & Directorate-General for Research and Innovation, 2022) and several member states have endorsed bioeconomy research and policy strategies since 2010. Numerous countries, such as China, India, Brazil, and South Africa, also have implemented bioeconomy policies and strategies to promote sustainability within their economies (Dietz et al., 2018; Wesseler & von Braun, 2017).

The concept of bioeconomy varies in interpretation and scope among countries and institutions. According to the European Commission (EC), the bioeconomy covers "all sectors and systems that rely on biological resources" and all economic and industrial sectors that "produce food, feed, bio-based products, energy, and services" (European Commission, 2018). The USDA defined the term "bio-based product" as "a commercial or industrial product (other than food or feed) that is composed in whole or in a significant part of biological products or renewable domestic agricultural materials (including plant, animal, and marine material) or forestry material" (U.S. Department of Agriculture, 2008). The definitions of bioeconomy across countries or institutions share many similarities. Agriculture, forestry, fisheries, food, pulp and paper production, as well as parts of the chemical, biotechnological, and energy industries, are all considered part of the bioeconomy (Wesseler & von Braun, 2017).

The bioeconomy is viewed as a key driver of sustainable development by sustainably utilizing biological resources, thereby enhancing social, economic, and environmental well-being (Calicioglu & Bogdanski, 2021; Ferraz & Pyka, 2023). The EU bioeconomy strategy's action plan aligns with 53 targets across 12 of the 17 Sustainable Development Goals (SDGs) (Ronzon & Sanjuán, 2020). The bioeconomy can have substantial impacts, which are effectively reflected in the broad range of SDGs (Heimann, 2019). Monitoring and evaluating the bioeconomy can help track progress on SDGs, especially in areas like economic growth (e.g., SDG 8), food security (e.g., SDG 2), and sustainable consumption (e.g., SDG 12) (Calicioglu & Bogdanski, 2021).

The bioeconomy differs from related concepts concerning sustainable development (D'Amato & Korhonen, 2021; Kardung et al., 2021), such as the "biobased economy," "green economy," and "circular economy." These terms partially intersect and share common sustainability and resource efficiency goals. The green economy is often considered an overarching concept aimed at improving human well-being and social equity, as well as reducing environmental risks and ecological scarcities. The bioeconomy is generally viewed as a subset of the green economy, focusing on economic growth and technological development through the sustainable use of biological resources. The bio-based economy involves converting biological resources into products and materials, including both innovative bio-based products and traditional ones like textiles and wood products. Complementary to the bioeconomy, the circular economy emphasizes recycling, reduction, and sustainable resource use to minimize waste. The synergies between the bioeconomy and circular economy concepts are significant. The term "circular bioeconomy," introduced by the EC and others, highlights the integration of both concepts and emphasizes the importance of applying circular principles to the bioeconomy (Kardung et al., 2021).

The conceptual framework discussed by Kardung et al. (2021) illustrates the dynamic process of the bioeconomy, highlighting the interconnectedness of various factors and actors involved. In the framework, driving forces, (re-) use of resources, policies, strategies, and legislation, as well as societal objectives, are integrated through the supply and use of biomass. Supply and demand are crucial driving forces in shaping the framework. Resource availabilities such as land, water, and labor impact the biomass market. Additionally, wastes/by-products are crucial in realizing a sustainable and circular bioeconomy. Policies, strategies, and legislation serve as instruments of governments to affect the bioeconomy. Within the biomass market, various supplies and uses of biomass are determined by the drivers and resource availability mentioned earlier. The interaction among drivers, policies, and resources influences the bioeconomy's demand and supply, ultimately contributing to its role in achieving sustainable objectives.

The concept of a circular economy aims to minimize waste and make the most of resources, but it faces several challenges and could benefit from learning from existing economic concepts. In the eighteenth century, François Quesnay and the Physiocrats emphasized the importance of agriculture as the source of wealth. The Physiocrats' focus on natural cycles and the flow of resources can be seen as an early precursor to circular economy principles. However, their model was limited to agricultural productivity and did not account for industrial and technological advancements. Johann Heinrich von Thünen developed a model to explain the spatial organization of agriculture around a central market. His model considered transportation costs and land use, highlighting the importance of location in economic activities. This systems approach can be applied to the circular economy by considering the logistics and spatial distribution of recycling and resource recovery facilities. However, von Thünen's model primarily addressed agricultural land use and may not fully capture the complexities of modern industrial economies. The price system, driven by supply and demand, is crucial in resource allocation. Prices signal

scarcity and value, influencing production and consumption decisions. In a circular economy, the price system can be leveraged to promote sustainable practices by internalizing environmental costs and providing economic incentives for recycling and reuse.

5.3 Measuring the Contribution of Bioeconomy to Sustainable Development

Measuring the contribution of the bioeconomy to economic growth and sustainable development is challenging due to its dynamic nature, which is affected by technological advancements, industrial progress, policy shifts, and other factors. Various approaches can be employed to measure the bioeconomy, each providing valuable insights and results.

5.3.1 Bioeconomy Value Added and Turnover

Measuring the contribution of the bioeconomy to economic growth requires understanding its share within the overall economy. One widely used approach involves using the system of national accounts, while input–output tables and statistical surveys are also commonly employed (Efken et al., 2016; Heijman, 2016). Based on MAGNET, a global forward-looking ex ante simulation model, the BioMonitor project of the European Union's Horizon 2020 (BioMonitor, n.d.), bridged the information gap in bioeconomy research by restructuring its existing data and modeling framework and projected the EU bioeconomy production trends. The project introduced new biochemical activities (biochemicals, biopharmaceuticals, bioplastics) to create a new virtual trade and "footprints" module with a state-of-the-art baseline.

Using 2020 as the base year, significant increases are anticipated in 2030 and 2050 across all relevant sectors. The total bioeconomy production is estimated to be €3294.576 million in 2020, €3647.336 million in 2030, and €4233.644 million in 2050. The largest subsector is Food & Food Service, with estimated values of €1576.375 million in 2020, €1786.446 million in 2030, and €2172.289 million in 2050. The biofuel-solid sector shows the most significant change, nearly doubling by 2050 compared to 2020.

BioMonitor also analyzed the scenarios where fossil fuel prices rise by 30% (30% case) and 50% (50% case) above the baseline in 2050, and both positive and negative impacts are observed. In the baseline scenario, the real GDP is projected to reach 159.76 in 2050, with the base year set at 2020 (=100). However, in the 30% case, the real GDP is expected to decrease by 0.47, and in the 50% case, by 0.74. On the positive side, total emissions for 2050 are projected to be 2628.32 $MtCO_2e$.

Nevertheless, emissions are forecasted to decrease in both the 30% and 50% cases, with reductions of 227.13 and 348.12 $MtCO_2e$, respectively.

Input–Output (IO) models map the inter-industry relationships within an economy by quantifying the inputs required by each industry to produce its outputs. An IO model depicts how the output of one industry serves as an input to another, forming a complex network of interdependencies across the pre-defined sectors/industries. To measure the bioeconomy size within an economy, various IO measurement methods have been introduced (Ronzon et al., 2024):

- The "output-based" approach quantifies the size of the bioeconomy in terms of socio-economic indicators, focusing on the bioeconomy nature of outputs, which is determined by the bio-based share of outputs (Ronzon et al., 2022). It also considers the bioeconomy relevance of intangible outputs; Lazorcakova et al. (2022) also includes environmental indicators in bioeconomy IO measurement.
- The "input-based" approach measures the bioeconomy value added generated by an industry in proportion to the bio-based inputs from primary industries (agriculture, forestry, fishery, aquaculture, and veterinary services) (Heijman, 2016).
- The "weighted Input-Output" takes into account the parameters quantified by the output-based and the input-based approaches (Kuosmanen et al., 2020),
- The "upstream-downstream" approach measures the bioeconomy value added within the industries by using IO flows between industries to calculate downstream and upstream value added by the bioeconomy (Cingiz et al., 2021, 2023).
- The Hypothetical extraction method quantifies how much the total economy would shrink if a particular sector is removed from the IO table (Miller & Blair, 2009).

These models provide measurement tools to analyze bioeconomy growth and size, and bridge the data gaps. An advantage of the IO methodology is that it builds on data collected in standardized statistics and is easily replicable, enabling temporal and spatial comparison of the bioeconomy and its development. Furthermore, by integrating environmental indicators into IO measurement models, investment decision-making mechanisms can be identified given the economic reversible and irreversible cost of environmental impacts of each industry's activity (Kardung, 2023).

Through the environmentally extended Input–Output (EE-IO) model, it is possible to track the flow of resources and pollutants. EE-IO assesses the upstream environmental impacts generated by downstream economic consumption and accounts for the environmental impacts in traded goods (Kitzes, 2013).

It is essential to go beyond analyzing the growth and size of the bioeconomy when measuring its progress. Tracking the dynamic processes that drive its development requires various indicators, which can be challenging for policymakers to consider altogether. Kardung and Drabik (2021) have created a theoretical framework to address this issue. This framework can accommodate any number of well-defined quantitative indicators, making it easier for decision-makers to assess the overall development of the circular bioeconomy. It achieves this by normalizing indicators with different units and dimensions and exploring patterns using Markov transition matrices. This approach helps in understanding indicators covering a bioeconomy's

economic, environmental, and social aspects. Furthermore, the framework enables the assessment of the overall development of the bioeconomy, the dimensions in which it is progressing or regressing the most, and the dynamic changes in the relative positions of individual indicators.

These models enable stakeholders such as policymakers and researchers to assess different industries' environmental impacts, develop sustainability indicators and investment decision-making mechanisms, and further develop strategies for promoting sustainable development and economic growth. Integrating economic and environmental data through IO modeling frameworks offers a valuable tool for advancing sustainable bioeconomy growth.

5.3.2 Material Flow Model

Modeling results can be linked with material flow models and vice versa. A material flow model is a tool that helps analyze how materials move through different processes within a system. The flow model results in a material flow monitor (MFM) and provides information on resource efficiency by integrating data on inputs, processing, outputs, transportation, and inventories. It also identifies areas for efficiency improvements and assesses environmental impacts. Additionally, it evaluates recycling strategies and waste management and helps plan logistics for material distribution.

The Netherlands serves as an illustrative example of an application of the MFM (Lucas et al., 2022). In 2018, the Dutch economy utilized nearly 450 Mt. of material resources, comprising primary resources, recycled materials, and those within materials, components, and products. Approximately a quarter originated from domestic sources such as natural gas, gravel, and agricultural products, while the remaining three-quarters were sourced from abroad, including fossil fuels, metals, and materials within products. Nearly half of these material resources were exported as finished or semi-finished products, like fodder converted into meat or metals processed into machine parts. Additionally, the Netherlands imported a significant volume of material resources, which were largely re-exported to other countries without substantial processing.

The Bio Flow Monitor (BFM) is a material flow model based on MFM and is used to identify indicators relevant to bioeconomy and circular economy policy (Delahaye et al., 2023). The MFM collects data on the whole economy from a database that includes integrated statistics, recording in the case of the Netherlands supply and use tables for 400 products and 130 sectors, including biomass. However, the MFM is unsuitable for estimating the bioeconomy, so the BFM was developed. Figure 5.1 provides an overview of the methodology for estimating the BFM. The monitor records biotic and abiotic supply and use tables, providing data on biomass usage by bio-based industries and filling data gaps regarding the use of biomass. Figure 5.2 illustrates biomass flows in the Dutch economy.

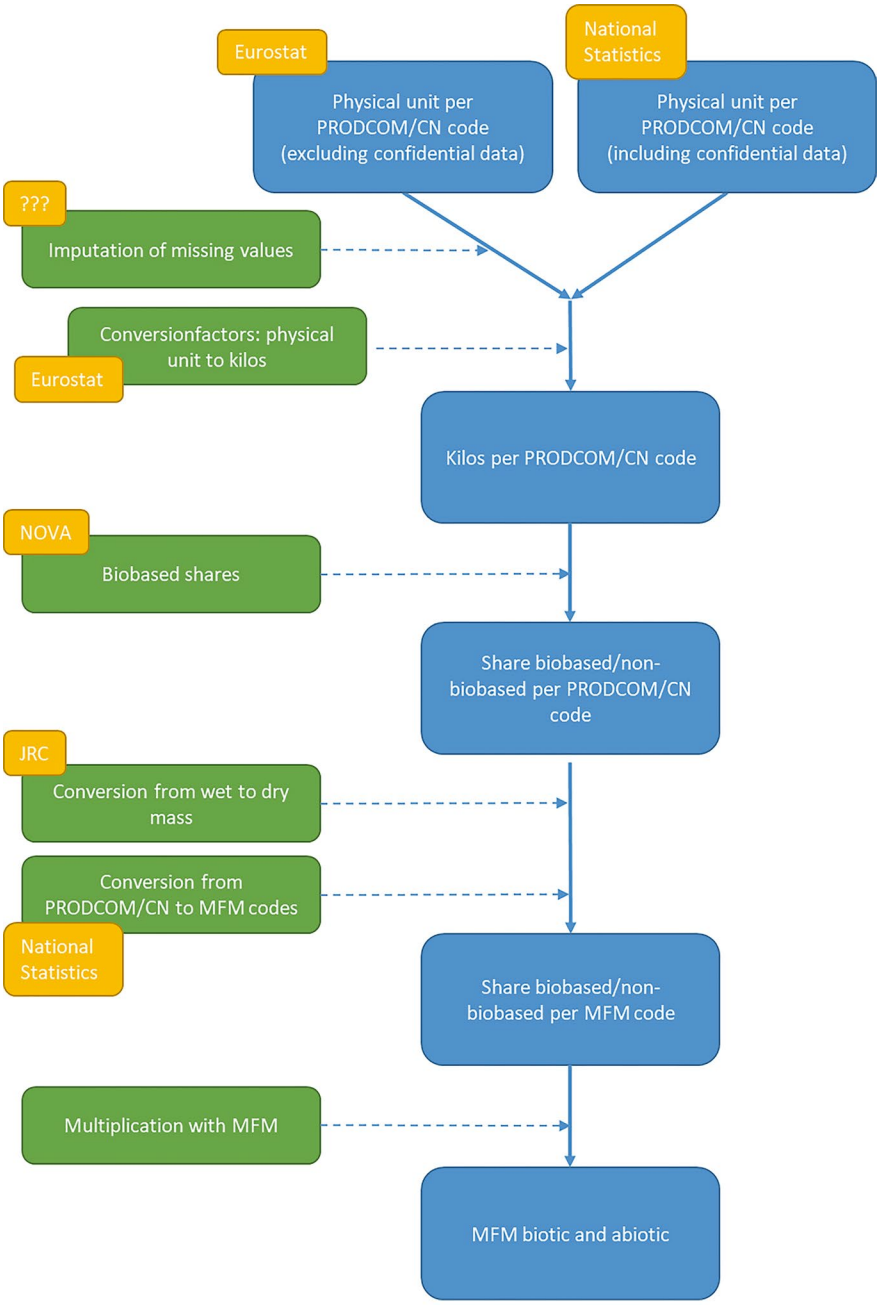

Fig. 5.1 Overview of methodology to estimate the Bio Flow Monitor. Note: Solid lines represent transitions from one stage of the process to the next. Dotted lines indicate help files that are used to make these transitions

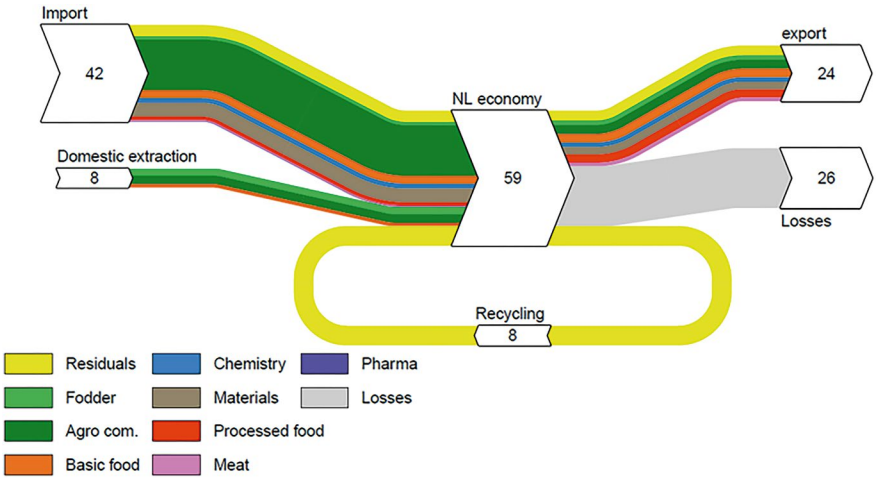

Fig. 5.2 Biomass in and out flows of the Dutch economy (kilotons dry matter), 2018

The BFM fills data gaps concerning bio-based industries' use of biomass and provides data on kilo biotic and abiotic production per economic sector. A key result is that in terms of weight, only 19% of the Dutch production could be considered part of the bioeconomy (biotic production) in 2018. Some biomass is obtained from domestic extraction and waste flows, while other biomass is obtained from trade with other countries. The BFM allows for calculating indicators that relate domestically extracted biomass to imported biomass, addressing the dependency on foreign countries. Figure 5.2 shows biomass flows in and out of the Dutch economy, revealing that the Netherlands is very dependent on biomass imports.

Within the BioMonitor project, the concepts of a MFM and a BFM applied in the Netherlands were replicated for Italy, Spain, Slovakia, and Latvia to reveal biomass flows and the most important biomass types and sources. Contrary to the Dutch results, domestic agricultural and forest biomass plays the most important role in the Slovak and Latvian economies. In these countries, the share of domestic agriculture in the total economy also decreases in terms of socio-economic indicators. Compiling a country's MFM or BFM from currently available public statistics is a challenge; it is only possible in close cooperation with national statistical offices (and other institutions) gathering detailed data.

The BFM also serves to assess the principle of cascading, which aims to derive the highest value from biomass through various processing stages. It helps identify the volume of dry matter per stage of the processing (cascading) pyramid, contributing to understanding the bio-based economy and biomass usage. Figure 5.3 shows the weight pyramid, indicating that agro commodities have the largest share with food processing, while pharma and chemistry-related bio-based products have the smallest share.

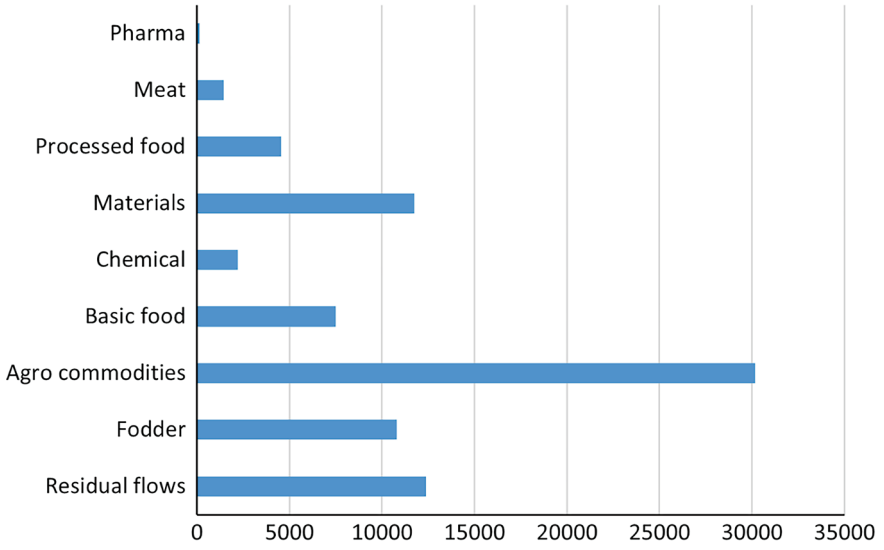

Fig. 5.3 Cascading of biomass (in mln. kilo), The Netherlands, 2018

In the future, other relevant indicators addressing societal problems could be derived from the BFM:

- Resource management: supply and use of biomass by sector.
- Climate change: greenhouse gas emissions per sector.
- Circular economy: use of primary versus secondary biomass flows.
- Substitution: use of biotic versus abiotic materials.
- Economic importance: value added/employment in biotic sectors relative to abiotic sectors.
- Losses: input biomass resource/output biomass product (or biomass waste output).
- Resource efficiency: value added per unit biomass use.

The BFM will also be integrated with carbon accounts. Carbon accounts are part of the SEEA-EA framework. International guidelines for setting up these accounts are led by the United Nations (UN). The Netherlands' carbon stock account is comprehensive in that all-important carbon reservoirs are included. There is a link between policy on circular economy (material use) and climate change (GHG emissions), as well as ecosystem services (sequestration) and natural resource dependency (fossil fuel extraction). Hotspots of carbon flows indicate the most efficient policy measures.

The impact of circular economy strategies on climate change mitigation depends on factors such as the amount of fossil-based carbon extracted from the environment, the quantity of carbon recycled or stored within the economy, the level of carbon emissions released into the environment, and the extent to which bio-based

carbon substitutes for fossil-based carbon. These strategies can be applied to various sectors or product groups within the economy.

Our evaluation of the Netherlands' bio-based economy revealed that it is still relatively small within the total economy. While some bio-based indicators have already been incorporated into Dutch circular economy policy, further development is needed. The BFM's integration with carbon accounts presents exciting potential for future policy applications.

5.3.3 Bio-Based Material Availability

Using material flow models is particularly interesting for modeling bio-based materials in the chemical and construction sectors. It is essential to measure bio-based material production to assess the potential of the bioeconomy. BioMAT (Bio-based MATerials) is a new consistent framework that aims to provide projections for the markets of bio-based materials, starting with bio-based chemicals, and for the respective feedstock needs for EU member states and EU27, up to 2030 and 2050. BioMAT operates as a module of the AGMEMOD (AGriculture MEmber state MODelling), focusing on the chemical industry (Sector code: C20) with full coverage of all bio-based products. It starts with data from PRODCOM codes and offers a stylized representation of value chains. The illustrative example groups the entire output of C20 into 16 product application categories, including two intermediates (Fig. 5.4). Additionally, BioMAT differentiates between ten types of bio-based feedstocks and links them to agricultural crop production in the EU via linkage to AGMEMOD (Sturm et al., 2023; van Leeuwen et al., 2022). The production of bio-based chemicals in the EU amounted to 43 million tons in 2018, accounting for 14 percent of the total output volume of the organic chemical industry. BioMAT breaks down how these materials were used as shown in Fig. 5.5. Biofuels are the biggest category (42%), followed by agrochemicals (21%), surfactants (12%), and cosmetics and personal care products (6%). Other uses make up smaller portions.

5.3.4 The Socio-Economic Impacts of Wastewater Sludge Valorization: The Case of Biofertilizers in Italy

A case study on tracing uncertain sustainability footprints from sewage sludge with application in agriculture used a hybrid IO assessment in the Northern Italian context. The biorefinery under study collects 165,000 tons per year of sludge from 45 wastewater treatment plants serving 226 municipalities. The sludge is further treated as a resource rather than waste and conditioned by sulfuric acid, lime, and gypsum to produce 160,000 tons of biofertilizers annually. Sewage sludge is a by-product of municipal or industrial wastewater treatment plants. Italy produces 3.1 million tons

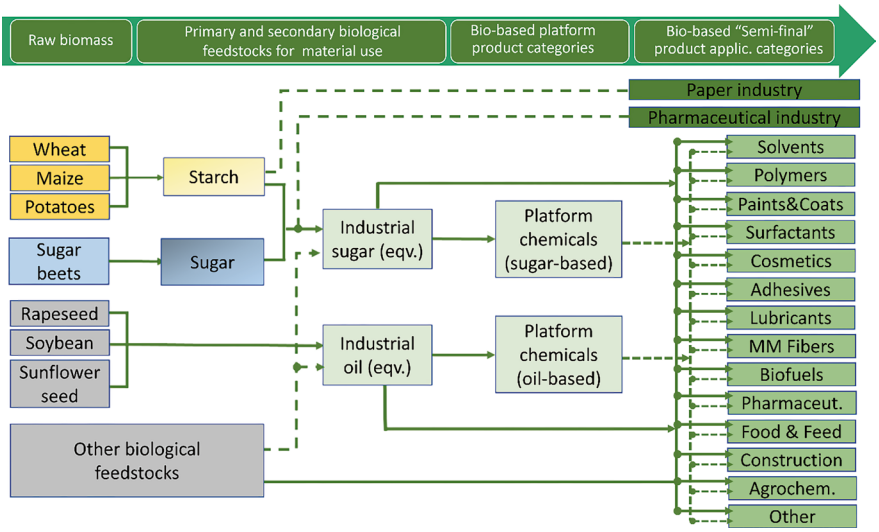

Fig. 5.4 Bio-based value chains covered in BioMAT. Source: Sturm et al. (2023). Note: Dashed lines are used for flows that are not the main focus of the BioMAT model (C20 "Chemical Industry") and/or are modeled in less detail: (1) "paper industry" and "pharmaceutical industry" do not belong to C20 (chemical industry), which is the main focus of BioMAT, and are considered as aggregates. (2) "other biological raw materials" are not covered in full detail in the AGMEMOD model, which provides information on the availability/supply (quantities, prices, etc.) of these feedstocks from the respective markets for raw materials

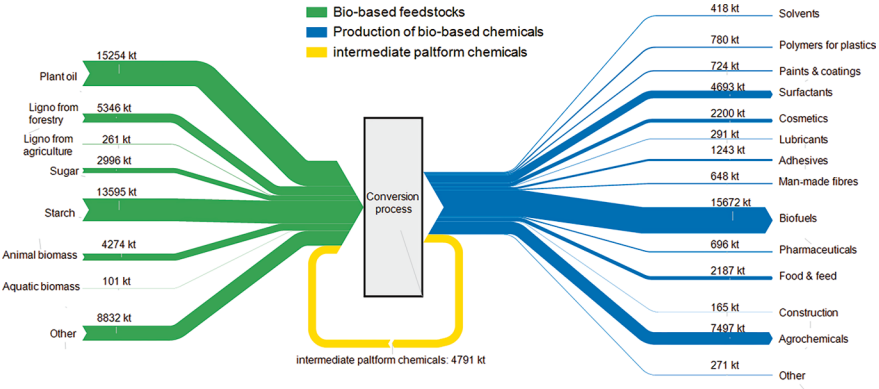

Fig. 5.5 Use of biological resources for production of bio-based chemicals in the EU in 2018. Source: Sturm et al. (2023)

of sludge (Tassinari et al., 2023) per year and 56.3 percent is landfilled. The case study aimed to assess organic fertilizers' sustainability footprints from sewage sludge production.

The case study concluded that there are confidentiality issues. Because of the type of information provided to the company, it was easier to collect the data, which was nevertheless collected at a level of aggregation that ensured the confidentiality of all relevant intellectual property. Thanks to the hybrid IO analysis, it was possible to overcome the data aggregation problem in useful tools such as supply and use tables. These tables, however, still lack details for bio-based productions.

Using a multiregional IO database has made it much easier to contextualize to a broader geographic level than local or national, quantifying the externalities of economic activity in foreign countries. A Monte Carlo analysis improved the generalizability and validity of the results, addressing inherent limitations of more common life cycle thinking approaches.

Many indicators for measuring the bioeconomy fit the hybrid IO framework, allowing a comprehensive approach for systematic impact quantification. However, not all indicators are readily measurable from basic monetary IO tables. Most indicators can only be handled using multiregional IO coupled with non-economic, physical data or physical IO tables. A final recommendation concerns the employment indicator. It is important to note that available data are reported by gender and by low-, medium-, and high-skill level groups. This information can be used as other useful sub-indicators to address a more thorough social assessment of the bioeconomy.

5.3.5 Bioeconomy and EU Regional Development

The transition to a bioeconomy is expected to create new job opportunities, although some sectors, like coal mining and fossil fuel extraction, may experience job losses. Biorefineries, which convert biomass into value-added products, are a crucial component in this transition, potentially promoting economic growth and employment in rural regions. Biorefineries produce biofuels, biochemicals, bioenergy, and other biomaterials, replacing fossil-based products. They can create new value chains and attract innovative technologies, thus fostering regional economic growth and employment. However, the introduction of biorefineries might also reduce employment in sectors involved in fossil-based production. The overall impact on local employment remains ambiguous.

Biofuels stand out as some of the most prominent and economically significant outputs of biorefineries. These include biodiesel, bioethanol, and advanced biofuels, which are essential for reducing greenhouse gas emissions in the transport sector. Within the European Union, biofuels accounted for the largest share, approximately 42 percent, of bio-based chemical production in 2018, according to the BioMAT model. Production of biofuels is expected to increase from approximately 14,000 million metric tons in 2018 to 18,000 million metric tons in 2030. Biochemicals, bioplastics, and biopolymers are also high-value products from biorefineries. Intermediate chemicals production is expected to increase from approximately 5000

miot in 2018 to 8000 miot in 2030, while surfactants and agrochemicals are expected to increase by 1000 miot or less (van Leeuwen et al., 2023).

Zhu et al. (2023) have used data from the EU Joint Research Centres (JRC) and the EU H2020 BioMonitor project, covering various types of biomass processing facilities across Europe over the last decade. A linear regression model was employed to assess the determinants of employment and their impact over time at the regional level, comparing regions with and without biorefineries.

Their findings indicate that biorefineries create direct employment at the facility and indirect jobs in farming and service industries. For example, a biorefinery in Hungary created 172 direct jobs and over 5000 indirect jobs. Regions with biorefineries exhibit higher employment growth compared to those without. The study found a positive correlation between the number of biorefineries and regional employment, even after accounting for other factors like population, income, education, and infrastructure. The employment impact of biorefineries is higher around the time of establishment and decreases over time due to the initial labor needs for construction and early operation phases.

By 2022, there were 2655 biorefineries in the EU, with Germany, France, and Sweden having the highest numbers. The Netherlands, Belgium, and Germany showed the highest density of biorefineries per km^2. The bioeconomy sector employed 2.56 million workers and generated significant economic value.

The study recommends improving data on biorefinery capacity, production, and status (e.g., operational, halted) to refine future analysis. Policymakers should consider the dynamic nature of biorefinery employment impacts and support regions transitioning from fossil-based to bio-based economies. Further research with more detailed econometric tools and data on small biorefineries could provide deeper insights into the regional impacts of biorefineries.

In conclusion, biorefineries have the potential to significantly contribute to regional employment and economic growth in the EU. However, their impact varies over time and across regions, necessitating continuous data collection and analysis to inform policy decisions and support the bioeconomy transition.

5.4 Future Opportunities and Challenges

The bioeconomy is being transformed by innovative technologies that enhance biomass production and enable new processing methods. Enhancing biomass production and processing is crucial to minimize concerns about the use of biomass for non-food purposes and, therefore, to promote the bio-based economy with a focus on bio-based materials and energy products. At present, this nexus persists, with the result that the production of bulk bio-based products, especially biofuels, is repeatedly questioned, while the production of bio-based products with specific properties (e.g., bio-based fine chemicals) is rather spared from such criticisms. Innovative technologies like synthetic biology are used to engineer microorganisms for the sustainable production of biofuels and bioplastics (Agarwal et al., 2022). Precision

agriculture employs GPS and drones to enhance farming efficiency, while advanced biomaterials are replacing traditional plastics, reducing reliance on fossil fuels. Bioremediation utilizes microorganisms to clean up pollutants, and cellular agriculture grows meat in labs, offering a sustainable alternative. Urban fishermen are adopting aquaponics for fish cultivation. Insect burgers provide a protein-rich and eco-friendly food option. Biological carbon capture harnesses algae to convert CO_2 into valuable products, while microbial electrochemical technologies generate energy from organic waste, benefiting the environment and the economy. Industrial hemp production provides opportunities for net-zero carbon building materials (Ahmed et al., 2022). These technologies are not only helping to protect the environment but also creating new economic opportunities in the bioeconomy.

Key research questions, such as achieving Net-Zero solutions, require cooperation among scientists, engineers, and policymakers. These questions involve exploring the most promising technological innovations across different sectors while addressing issues related to intellectual property rights to encourage widespread dissemination. Numerous emerging technologies for the circular bioeconomy rely on advancements in biological sciences, including CRISPR-Cas. Implementing these technologies is subject to stringent regulations, and notably, their use in plant breeding has become challenging within the existing regulatory framework. Therefore, it is also momentous to revise regulatory barriers to employ these innovations. It is essential to develop monitoring tools at both national and international levels, which involves identifying key indicators and enhancing data analytics for precise progress tracking while also establishing transparent governance mechanisms. Harmonizing national and international policies requires resolving gaps and overlaps, designing multi-level governance frameworks, and leveraging international organizations to promote coherence. This entails reconciling divergent interests, standardizing policy instruments, and overcoming political and institutional barriers through capacity-building and diplomatic negotiations.

To ensure the bioeconomy sector not only survives but thrives through innovation, it is crucial to focus on the next generation of professionals (Carrez & Rupp, 2023). This requires aligning educational programs at all levels with the bioeconomy skill and training needs. We can effectively identify and address skill and knowledge gaps by monitoring and assessing higher education. It is also essential to track students' enrolment and graduation rates in bio-based and bioeconomy courses, as well as their subsequent career paths in the industry. Collaborating with higher education institutions to qualitatively evaluate and update curricula will help ensure that course content meets industry requirements, making necessary adjustments along the way. In the BioMonitor project, four early-stage researchers were hired to generate human capital for future exploration of the project results.

Indicators simplify the intricate complexity of describing the bioeconomy. They also represent a compromise regarding what can be quantified, the type of data collected, and its quality. The implication is that indicators and related methodology should be considered value-neutral. A link to specific policy objectives should only be made if they explicitly reference some indicators and associated methodology. For example, it would not be prudent to say that an increase in all the indicators that

mark the transition toward bioeconomy means that all possible aspects of the transition have been accomplished.

The design of modeling toolboxes cannot be completely separated from other issues, such as data availability. Throughout the design process, it is important to factor in data availability since, in numerous instances, public databases do not contain data on bio-based textiles, plastics, chemicals, pharmaceuticals, or other products. Additionally, the available data series are often brief and incomplete due to confidentiality issues, missing product codes, or the relatively short time that some bio-based products have been on the market.

Developing effective and reliable methods for gathering data to monitor and assess the bioeconomy is challenging, but there has been significant progress in this area. Cingiz et al. (2021) created a model incorporating upstream and downstream connections using IO tables. Kuosmanen et al. (2020) have developed a hybrid modeling approach to reconcile various quantitative techniques for estimating value added and employment in the EU and its Member States. Regarding data collection through case studies, there is a need to establish standardized research protocols that promote transparency and reproducibility in bioeconomy case studies (Tassinari et al., 2021).

The combination of simulation models for the EU bioeconomy can capture several cross-cutting issues of a bioeconomy transition, considering competition and interactions between economic sectors. The results of modeling toolbox simulations can provide policymakers with the critical knowledge currently missing for further progress toward a circular and sustainable bioeconomy. Bioeconomy models have been extended to include additional bio-based sectors, which addresses the need to recognize water as a key factor of production and the emerging importance of the developing bio-industrial sectors. Moreover, the model has been enhanced in terms of model indicators for the bioeconomy. A new multiregional partial equilibrium for innovative-based processed product markets addresses the extent to which bio-based products can substitute their fossil-based carbon content with bio-based carbon content.

Developing a strong and effective framework for creating statistics and modeling tools for the bioeconomy is a huge undertaking. The bioeconomy is a broad strategy that addresses various economic, social, and environmental challenges at the same time. Defining the policy scope for the bioeconomy and designing related baselines and scenarios is not a simple task. It is important to consider the trade-offs between policies. The links between policies have become stronger, making assessing their objectives and elements more complicated.

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Chapter 6
Principles, Implementation, and Policy Challenges for a Circular Bioeconomy

Marty Matlock

6.1 Introduction

The concept of the circular bioeconomy represents the convergence of two interrelated concepts: the circular economy and the bioeconomy. This convergence emerged from projections of resource scarcity, analyses of ecosystem impacts from human activities, and expanding fragility of food and agriculture supply chains. The formal economic concept of circularity is more than two centuries old. The conceptualization of natural resource economics by Francois Quesnay, a French physician, became known as the Physiocrat's School of Economics in the mid-eighteenth century (Cingiz & Wesseler, 2019). The innovation of the physiocratic framing was the explicit dependence of wealth generation on natural resource extraction, the so-called Natural Way (see Chap. 2). The inherent circularity of extraction and investment in agricultural production systems was informed by Chinese philosophy, so the concepts are more than a thousand years old (Maverick, 1938; Min, 2025). In fact, Quesnay was often referred to as "the Confucius of Europe," such were the influences of Chinese thought on his work.

The models for circularity in natural resource extraction expanded with analyses of ecological constraints of exploited resources like fisheries (Giampietro et al., 2025). Advances in quantifying mass and energy flows began in 1966 when Keneth Boulding (Boulding, 1966) framed the resource limitations of the biosphere as "spaceship Earth." Ecologists like H.T. and Eugene Odum began simulating ecosystem mass and energy flows in the 1970s, expanding the discipline of systems ecology to include human extractions and disruptions of ecosystems (Odum, 1971a, 1971b, 1983). The global recognition of Earth's limited resources, especially bioresources, was further elevated in The Club of Rome's report "*The Limits to Growth*"

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(Meadows et al., 1972). This report was unequivocal in its warning that resource depletion and ecological damage from economic growth would result in catastrophic social and political failure. *The Limits to Growth* became a polarizing nexus for political and economic debate because it pitted economic expansion against environmental conservation. This tension persists 50 years later.

The circular economy concept manifested as the field of Industrial Ecology in the late 1980s (Frosch & Gallopoulos, 1989). Industrial ecology proposed that industrial systems should consider all materials valuable and thus minimize waste through reduction and recycling. Pearce and Turner (1990) expanded this concept by linking the economic system with the industrial system and coined the term "circular economy," though Walter Stahel used the term "closed loop economy" as early as 1970 (Stahel, 2020). The circular economy concept became a mainstream policy framework in 2010 when the Elen MacArthur Foundation made it a singular focus, defining it as "an industrial system that is restorative or regenerative by intention and design" (Ellen MacArthur Foundation, 2013, 2019).

The term "bioeconomy" emerged in the 1990s as a category of economic activities associated with advances in biotechnology (Enriquez-Cabot & Goldberg, 2000, Bugge et al., 2016). The OECD (Organization for Economic Co-operation and Development), a forum and knowledge hub for data, analysis, and best practices in public policy, expanded the concept of the bioeconomy to include biological resources in their report "*The Bioeconomy to 2030*" (OECD, 2009). The formal definition of the bioeconomy emerged from debate over the European Commission's *Bioeconomy Strategy* as "the production of renewable biological resources and their conversion into food, feed, bio-based products and bioenergy" (European Commission, 2012), updated in 2019 with a goal to transition the European economy into a circular bioeconomy by 2050(European Commission, 2019). This chapter covers the principles of the circular bioeconomy, current implementation strategies, and necessary policy frameworks for broad adoption of these principles and frameworks.

6.2 Principles of the Circular Bioeconomy

The concepts of circular economy and bioeconomy are clearly aligned in their valorization of renewable and recycled resources, waste minimization, and energy use efficiency. The European Commission's, 2018 update of the *Bioeconomy Strategy* explicitly advocated for "a sustainable and circular bioeconomy" (European Commission, 2018, 2022). Other definitions have emerged but generally align with "an economy where the value of bio-based products, materials and resources is maintained for as long as possible, and the generation of waste is minimized" (Giampietro, 2019). Subsequent frameworks for assessment and implementation have followed these formalizations of the circular bioeconomy, including The Circular Bioeconomy Alliance (launched by King Charles III), the European Forest Institute (Hetemäki et al., 2022), and the Food and Agriculture Organization (FAO)

frameworks for circular bioeconomy in forestry, agriculture, and food systems (FAO, 2022).

The convergent evolution of the concepts of the circular economy and the bioeconomy, resulting in the circular bioeconomy framework, informs its defining principles. These fundamental principles were strongly influenced by European Commission policies, and include economic systems that:

1. *Utilize Renewable Resources*. The circular bioeconomy prioritizes renewable biological resources as primary inputs for materials, chemicals, energy, and products over fossil fuels and other finite resources (Carus & Dammer, 2018). Renewable resources are coupled with mass and energy flow in the biosphere and geosphere so that extraction and replacement reach equilibrium.
2. *Implement Cascading Use.* Circular bioeconomy elements should eliminate waste by keeping bio-based resources in use for as long as possible through cascading use (using materials at their highest value, then repurpose for lower-value applications) such as biomaterial recycling back to the biosphere, especially carbon and nutrients, is key to circularity in the bioeconomy (Bezama, 2016). The concept of waste is anathema to the concepts embodied in the circular bioeconomy, as all mass and energy have value and should be understood as part of the circular process (D'Amato et al., 2020).
3. *Advance Regenerative Design.* Circular design requires intentional designing out waste processes and products by turning biological waste and residues into valuable products (Ellen MacArthur Foundation, 2013, 2019). The concept of regenerative design was explored extensively by Lyle almost 30 years ago (Lyle, 1996) and was strongly influenced by the work of Odum (1983). He argued that most systems designed and constructed by humans are degenerative in that they extract energy and resources from nature and do not return them. He argued for the design of self-renewing systems that regenerated through a continued replacement of energy and materials in its operations.

These fundamental principles are very broad and thus often difficult to operationalize. Dissecting them into Biological and Technical Cycles can be helpful in discerning opportunities for innovation and transformation of linear systems to circular systems (McDonough & Braungart, 2002). Both categories of economic cycles attempt to reconcile economic, environmental, and social dimension of sustainability (Metic et al., 2021, Fig. 6.1). The diagram in Fig. 6.1 representing the relationship between biological and technical cycles is often referred to as the Butterfly Diagram.

6.2.1 Biological Cycles

Biological cycles utilize materials from the biosphere and return them to the biosphere. In Life Cycle Assessment, this is the Biosphere. Biological Cycle products are generally biodegradable or bio-transformable to other uses (Fig. 6.1). The

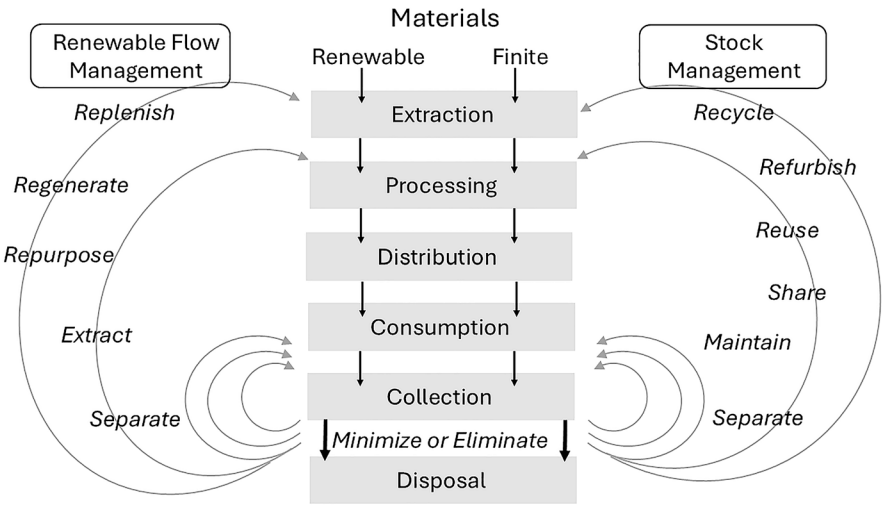

Fig. 6.1 Technical and biological cycles in circular bioeconomy (https://www.ellenmacarthurfoundation.org/the-circular-economy-in-detail-deep-dive)

constituents of these products are not just organic (carbon-based) materials but include minerals as well. Carbon-based biocycles often include a post-use treatment phase like anaerobic digestion to extract biogas (methane) for energy use, and aerobic digestion to concentrate nutrients like nitrogen and phosphorus for regenerating soils. Biological cycles also include higher level biological processes such as ecosystem services, which can be preserved and restored through regenerative design (Seruga et al., 2022).

6.2.2 Technical Cycles

Technical cycles are processes and products that humans create. In Life Cycle Assessment, this is the Technosphere. Technical Cycle products are generally not biodegradable and are not consumed but rather have a use phase followed by a recycled phase then disposal phase, typically in landfills (Fig. 6.1). Examples include petrochemical plastics and polymers, wood-plastic composites, solvents and adhesives, electronics, and metal products that are not recycled. Technical Cycles become more circular through longer use phases and more aggressive material recovery process through recycling. A key difference between Biological and Technical Cycles is products in Technical Cycles cannot be returned to the biosphere without reduction to elemental components because they are not biodegradable and constitute pollutants.

6.3 Implementing the Circular Bioeconomy

Implementing circular processes in the bioeconomy will require strategies specific to each sector. The bioeconomy can be categorized into three sectors based on the components of the biosphere from which they originate: Agriculture and Food Systems, Forest and Wood Products, and Bio-based Resources. Each of these sectors contributes explicit elements to the global bioeconomy, though like all bioeconomy components they overlap considerably. Each sector and challenges for circularity are summarized below.

6.3.1 Agriculture and Food Systems

Resources extracted from the biosphere such as food and agriculture products are the largest sector of the bioeconomy. Almost half of habitable lands (45%, or 48 million km^2) are used for agricultural production (Fig. 6.2). Of that land area, 16% (8 million km^2) is used for cropland and 80% (38 million km^2) is used for livestock production. The opportunities for increasing circularity in the agriculture and food systems are very broad, in part because of the extensive nature of the enterprise. The following strategies provide opportunities for increasing the circularity of the global agricultural and food system.

1. *Regenerative Agriculture*. Regenerative Agricultural Practices focus on minimal soil disturbance, keeping soil covered, maintaining living roots year-round, increasing biodiversity through cropping system diversity, integrating livestock with cropping systems, and reducing synthetic inputs (Khangura et al., 2023).

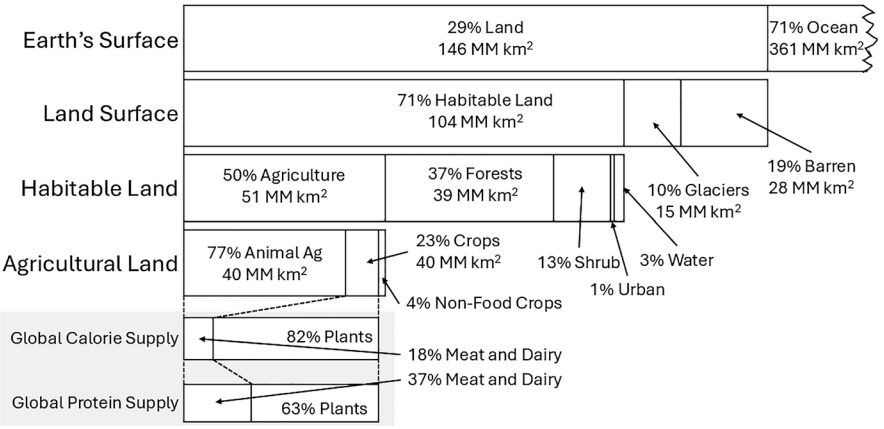

Fig. 6.2 Global land use for food production (Ritchie et al., 2023)

Regenerative agriculture emphasizes increased soil resiliency, achieved through returning organic matter to the soil. The benefits of these practices include increased soil tilth, reduced pest pressure, increased water holding capacity, and increased fertility (LaCanne & Lundgren, 2018). Under some conditions, carbon sequestration in the soil could be increased significantly (Minasny et al., 2017) though more research is needed to define the conditions that lead to that outcome.

2. *Food Waste Valorization*. Food waste remains one of the major challenges of circularity in the bioeconomy. Food waste is defined as food that is discarded or lost along the supply chain (production to consumption) that is not consumed. These products are disposed of in landfills or waste treatment systems, used for animal feed, or composted and returned to soil as amendments. The mass of food that wasted is staggering; as much as one third of all food produced, processed, and distributed for human consumption, or 1.3 billion tons, is wasted each year (Tropea, 2022). The breakdown of food waste sources by mass is roughly 26% from the drinks industry, 21% from the dairy industry, 14.8% from fruit/vegetable production and processing, 12.9% from cereal processing and manufacturing, 8% from meat product processing and preservation, 4.3% from manufacturing and processing of vegetable and animal oils and fish product processing and preservation, with the remaining 12.7% from other sources (Nayak & Bhushan, 2019). Creating value (valorization) for these waste products could result in numerous alternative pathways for reduction and reuse, in alignment with the principles of circularity (Fig. 6.3).
3. *Nutrient Recovery*. Bio-based fertilizers in production of food and agriculture products reduce reliance on the Technical Cycles and increase circularity of the food and agriculture system (Chojnacka et al., 2020). Recovered food waste and by-products can be converted to soil amendments and fertilizers to return macro-nutrients (Nitrogen (N), Phosphorus (P), and Potassium (K)) as well as carbon and micro-nutrients to the soil (Fig. 6.4). The European Commission has set a goal of 30% reduction of non-renewable resources in fertilizer composition in order to provide an economic incentive to recover and recycle bio-waste materials.

6.3.2 Forestry and Wood Products

Waste materials generated from production and use of forestry and wood products are the second-most significant mass of biomass waste generated globally. In 2020, global wood products totaled 465 million m^3 sawn wood, 367 million m^3 wood-based panels, and 401 million tons of paper and paperboard (Forest Research UK, 2022). The amount of waste materials generated at each stage (logging, milling, processing, construction, and end of life) are estimated to be as high as 30% by volume (Gayda, 2023). Because wood product wastes are easily converted to energy sources, economically viable products made from these wastes have emerged in the past decade (Langholtz et al., 2024). Mill residues are utilized for on-site energy

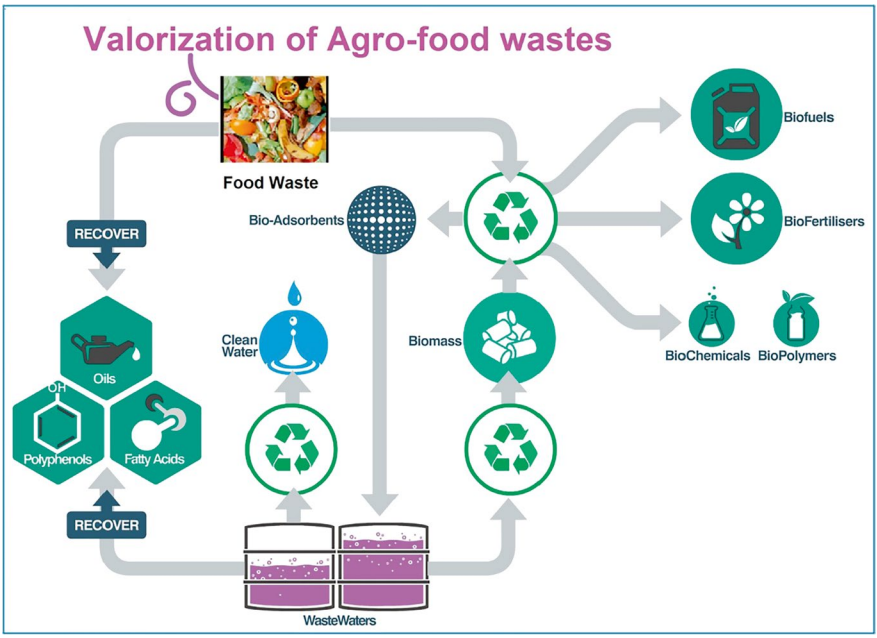

Fig. 6.3 Valorization of food waste, from Nayak and Bhushan (2019)

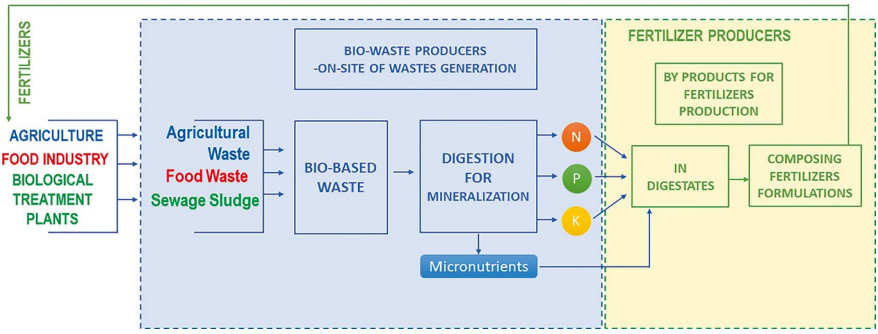

Fig. 6.4 Biofertilizer production from bio-waste, from Chojnacka et al. (2020)

production to dry timber products and heat water. Wood pellets are exported around the world as a replacement for coal. Advances in adhesives and binders have created expanding products made from wood fibers, including wood-based composite panels (WBCPs), medium density fiberboard (MDF), and oriented strand board (OSB) (Garcia et al., 2024). The emergence of mass timber architecture has resulted in increased efficiency in utilization of dimensional softwood sawn boards. Mass Timber Construction (MTC) utilizes engineered wood beams, posts, and panels constructed of dimensional lumber laminated in various configurations (Abed et al., 2022). Low-grade wood waste has the potential to be used to create biochar, an

emerging soil amendment that could sequester carbon and increase soil fertility (Wang & Wang, 2019). Economic value of these processes drives circularity in forestry and wood products, with new innovations emerging daily (Gagnon et al., 2022).

6.3.3 Bio-Based Resources

Bio-based resource supply chains utilize biological resources as inputs to produce food, feed, fiber, fuel, and other materials. The focus of bio-based resource production has been valorization of waste but emerging markets are driving primary production of feedstocks for some bio-based processes. The categories of processed biomass in bio-based industries include Bio-Energy Production and Bio-Based Chemicals and Materials (Leipold & Petit-Boix, 2018). These two sectors of the bioeconomy include established supply chains as well as emerging products. In most cases, the processing necessary to take low value biomaterials and convert them to high value products requires significant inputs of energy and technology (Fig. 6.5, Ondrasek et al., 2024). While these processes create circularity in the bioeconomy, life cycle assessment of some sustainability metrics, particularly greenhouse gas emissions per unit of production, may be significant.

1. Bio-Energy Production is energy derived from biological sources or biomass (Owusu & Asumadu-Sarkodie, 2016). Humans have been converting biomass to energy for as long as we have been a species. However, geochemical and petrochemical energy sources have dominated the human energy use portfolio for the past 300 years, resulting in a significant transfer of carbon from the geosphere to the atmosphere. Converting biomass to fungible energy, especially liquid fuels, reduces net greenhouse gas emissions by converting atmospheric carbon into biologic carbon for combustion as fuel. Bioenergy provides almost 55% of global renewable energy, representing over 6% of global energy supply (IEA, 2024). Biomass is converted to fungible and concentrated energy through thermochemical conversion and biochemical conversion. *Thermochemical conversion* processes include pyrolysis, using high temperature and pressure in the absence of oxygen to create gas, oil, and biochar, and gasification, which uses heat and chemical processes to convert biomass to gas (Canabarro et al., 2013). *Biochemical conversion* utilizes biological processes to chemically transform biomass into high energy molecules. The most common biochemical conversion processes are anaerobic digestion and fermentation. Anaerobic digestion uses microbes to convert biomass under low to no oxygen conditions into methane. Fermentation uses microbes to convert sugars from biomass feedstocks to liquid biofuels such as ethanol.
2. Bio-Based Chemicals and Materials are products derived in part or fully from biomass. Expanding bio-based chemicals and materials is a priority of the European Union under the European Green Deal, with a goal of creating circular bio-based solutions that drive the EU toward zero pollution by 2050 (EC, 2025).

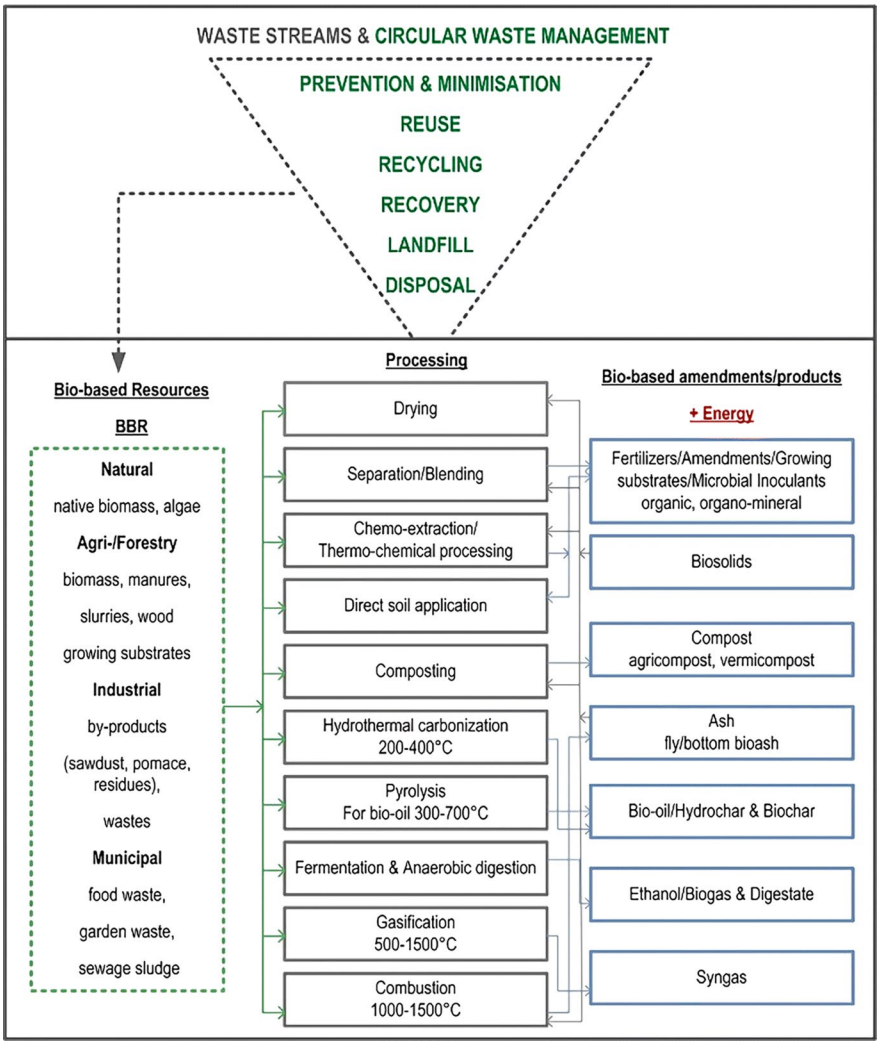

Fig. 6.5 Processes to create products from bio-based resources, from Ondrasek et al., 2024

Bio-based chemicals include organic acids, sugars and derivatives, alcohols, and polyols (Van Schoubroeck et al., 2018). Bio-based polymers include biologically derived plastics, composites (see mass timber from Forest and Wood Products), and vitrimers (Rosenboom et al., 2022). Bio-based materials are an emerging class of materials produced from biomass feedstocks rather than petroleum-derived materials (Cywar et al., 2022). Bio-based materials are often synthesized from bio-based polymers. The categories of bio-based materials include:

(a) Natural biopolymers such as cellulose, starch, proteins, and chitin.
(b) Processed biopolymers derived from biological monomers but processed to create polylactic acid, polyhydroxyalkanoates, and others.
(c) Bio-based composites which combine bio-based matrices with reinforcing elements such as cellulosic fiber and other bio-based materials.

Bio-based materials are recyclable, biodegradable, and generally have lower environmental and human health impacts than their petrochemical alternatives. They also provide an economic demand for biomass that may be considered waste in agricultural or forest product supply chains. The application of biomaterials in medical applications is a rapidly developing area of innovation (Baranwal et al., 2022). Research is needed to improve performance across many biochemical and biomaterial product categories to improve performance to compete with petrochemically derived alternatives.

6.4 Policy Framework for a Circular Bioeconomy

Developing and implementing policies that support a circular bioeconomy begins with understanding the barriers for circularity in the bioeconomy (Salvador et al., 2022). The primary barriers include lack of financial resources, especially venture capital, and price competitiveness with linear product offers. The drivers for innovation and implementation are therefore public policies and programs that incentivize circular bioeconomy implementation. The global leader in policy implementation has been the European Commission through the adoption of the new Circular Economy Action Plan (European Commission, 2015). The tools available to the European Commission are the same as for any government and include implementation of strategic incentives and critical restrictions. Incentive structures include instruments such as subsidized finance, tax incentives, and technical support. Restrictions include trade restrictions, tax penalties, and regulations. Effectively balancing between these policy instruments requires integrated strategies across policy domains (circular economy, climate, agriculture, energy, and industrial policy, for example) (Muscat et al., 2021).

6.4.1 Challenges of Policy Implementation

The risks of governmental intervention in complex supply chain economics are written in failed policies across history. Unintended consequences due to changing conditions in non-linear processes, intentional gaming of programs by bad actors, and marginal price plasticity are constant hazards to effective manipulation of complex markets. The most predictable challenge will be rebound effects where the low value waste becomes a high value feedstock. The economic viability of the bioproduct becomes a challenge when the feedstock prices escalate. Even more insidious is

the potential to drive production of what was a waste product because of the emergence of a market, resulting in unsustainable extraction of biomass from the environment (Ramcilovic-Suominen & Pülzl, 2018). Similarly, when bioproducts are introduced to the market at lower prices than the alternative products they could result in increased consumption, resulting in a demand-driven escalation of biomass extraction (Salvador et al., 2022). Markets can be delicate and chaotic systems that have limited buffers. Effective implementation of policies to advance circular bioeconomy practices and products will require extensive feed-forward and feedback assessment and monitoring to balance outcomes.

The European Commission updated bioeconomy strategy reiterated the five goals of the EU strategy (European Commission, 2019):

1. Ensure Food and Nutrition Security
2. Sustainably Manage Natural Resources
3. Reduce Dependence on Non-Renewable Resources
4. Mitigate and Adapt to Climate Change and
5. Strengthen European Competitiveness and Create Jobs

The EU revised the circular bioeconomy monitoring framework in 2022 to establish the EU Bioeconomy Monitoring System to assess the progress toward circular bioeconomy implementation. The revised framework calls for "application of and correlation towards life cycle assessment (LCA) and sustainability of biomass used, and guidance on the use of existing standards for the end-of-life options" (European Commission, 2022).

6.4.2 Assessment and Monitoring of Circular Bioeconomy Systems

Measuring the progress of global bioeconomy supply chains toward circularity shares the same challenges as measuring progress toward any sustainability goals. When considering the assessment of the United Nations Sustainable Development Goals (SDGs), Maurice (2016) highlighted the difficulty in implementing common metrics across indicators as broad as SDG 17. The consensus across interdisciplinary global program leaders was that assessment and monitoring infrastructure was not adequate to support even the highest level of evaluation of improvement across most SDGs. Assessing and monitoring effectiveness of circular bioeconomy programs and policies will face similar challenges.

Life cycle assessment (LCA) based approaches to measuring environmental impacts are the most effective (Lokesh et al., 2020). The LCA methodology is well established and is adequately flexible to cover any process or product in the bioeconomy. LCA is an accounting scheme based on scientific and engineering principles of material and energy flows and is constructed as a set of linked unit processes. Each unit process accounts for the material and energy, raw material consumption, and emissions to the environment necessary to produce a product or

service. The standard procedure for conducting LCA is elaborated in a suite of international standards (ISO, 2006a, 2006b). ISO 14040 defines principles and frameworks and provides a clear overview of the practice, applications, and limitations of LCA to a broad range of potential users and stakeholders, including those with limited knowledge of LCA. ISO 14044 stipulates specific requirements and is designed to prepare, create, and critically review life cycle inventory (LCI) analysis. It also offers guidance on the impact assessment phase of LCA, that is, the life cycle impact assessment (LCIA) and on the interpretation of LCA results, as well as the nature and quality of the data collected.

The basic steps of an LCA are: (i) goal and scope definition, (ii) develop the life cycle inventory (LCI), (iii) conduct the life cycle impact assessment (LCIA), and (iv) interpretation of results (Fig. 6.6) (ISO, 2014). LCIA is the phase in the LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system. In this phase, inventory data on inputs and outputs are translated into indicators about the product system's potential impacts on the environment and the availability of natural resources. The last stage of an LCA is the interpretation of the results of the LCI and LCIA according to the goal of the study. Interpretation allows the results of each of the previous steps to be placed into the system context and to identify the key factors for environmental decision-making.

Systems analysis methods like LCAs require significant data to inform unit process mass and energy flows, and to characterize impacts across environmental endpoints. These datasets are the product of standardized monitoring and reporting across every sector of the bioeconomy. This infrastructure will need to be developed, much like the SDG reporting infrastructure, in order to evaluate the legitimacy of circularity claims and the intentional and unintentional impacts of products and processes (Gursel et al., 2023). Bioresources must be produced and harvested

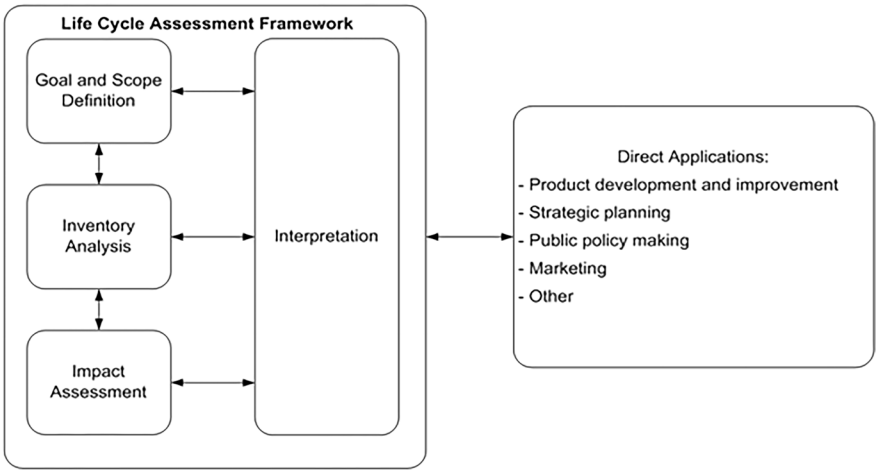

Fig. 6.6 Stages of an LCA (from ISO, 2006a)

sustainably to contribute to circularity. Measuring this characteristic is complex, requiring judgment across environmental metrics such as greenhouse gas emissions, water use, land occupation, energy use, and others. Bioresources degrade in quality with use and time, resulting in cascading value as they are cycled back to the biosphere. Measuring the cascade costs across a sector of the bioeconomy is complex, requiring new methods of monitoring and modeling products in the use and cascade phases of their life cycles. Bioresources are extracted from the biosphere and so must be returned to the biosphere at end of use, but where and when they are returned impacts the ecosystems from which they are extracted. The impacts of extracting carbon, nitrogen, phosphorus, potassium, and other nutrients as bioproducts must be assessed to achieve sustainable production, a key element of circularity (Navare et al., 2021).

6.5 Conclusions

Creating a bioeconomy to replace the current fossil fuel economy is critical if we are to reduce greenhouse gas emissions to levels necessary to sustain human prosperity. Making the bioeconomy circular is essential to preserve other life on Earth, especially in critical habitats. The changes in global economic systems that are necessary to valorize bioresources and reduce wastes are not trivial. The critical challenges for implementing policies and practices that move the global bioeconomy from linear include not only environmental policies, but social equity issues as well (Stegmann et al., 2020). The innovations necessary to make the transition from linear to circular utilization of bioresources will likely come from public–private partnerships driven by local and regional environmental concerns (Paes et al., 2024). The recent implementation of Life Cycle Thinking integrated with expansion of global supply chain databases and LCA methods has made transition to a circular bioeconomy plausible (Ramos Huarachi et al., 2023).

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Chapter 7
Regenerative Agriculture Bioeconomy: A Concept Facilitating Agriculture Transition from Circular to Regenerative Systems

Kaitlyn Daniels, Ian Bobbett, Charles Cao, Wendy L. Tate, and Jie Zhuang

7.1 Circular Agriculture and Circular Bioeconomy

Circular Agriculture (CA) and Circular Bioeconomy (CB) have gained prominence because of sustainability movements and economic principles. Policymakers, researchers, and organizations have collectively developed these sustainable concepts over time (Carus & Dammer, 2018). CA is focused on resource reuse within traditional farming practices with sustainability goals in mind, such as balanced ecosystems and reduced carbon footprints (Palahí, 2020).

CA is designed to reduce waste and chemical dependency while maximizing resource efficiency and enhancing soil fertility. Its main objective is to close resource loops, like that of water, nutrients, and energy. It does this by incorporating crop and livestock structures to reuse agricultural by-products. For example, animal manure from a cow can be used as organic fertilizer for crops like hay. This hay can feed the cows and other livestock and be converted into biogas from the crop residue. This approach reduces farmers' need for synthetic fertilizers while promoting soil fertility and biodiversity. The United Nations Food and Agriculture Organization (FAO) and agricultural researchers have long advocated circular approaches in agriculture (Khan & Ali, 2022).

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CB guides the transformation of renewable biological resources and waste materials into high-value products (Carus & Dammer, 2018). The products include food, animal feed, bio-based goods, biofuels, pharmaceuticals, and plastics, to name a few. By taking biological resources and applying them to economic principles with circularity in mind, a circular bioeconomy produces sustainable goods and services by providing value to waste and biomass (Abbas et al., 2023). The concept of CB was developed on the ideas of Walter Stahel and Michael Braungart, who conceptualized the "cradle-to-cradle" model by expanding on the ideologies of circular economy with a biological aspect (Mohajan, 2021). In addition to these pioneers, organizations like the European Commission helped pave the way for CB by enacting policies to attain sustainability and carbon neutrality within the environment (Cingiz et al., 2025). Over the last two decades, Europe has shown significant interest in increasing its CB strategies, something that the United States has started to lag on due to a multitude of reasons, including the lack of knowledge and communication of the strategy at hand (Gallo & Kuiken, 2022; Marshall et al., 2023; The White House, 2022). One country leading these processes effectively and to its full potential is the Netherlands, one of the most carbon-neutral and sustainable countries in Europe and the entire globe. Public engagement involves diverse forms of public and civil society participation, and it is crucial to understand the specificities of how difficult it truly is to introduce such a progressive, sustainable framework within a particular region (Lynch et al., 2020).

Circular agriculture focuses on sustainable agricultural farming practices for waste reduction and nutrient recycling, along with crop rotation, composting, and integrated livestock-crop systems for resource use optimization. In comparison, CB is a broader concept that applies circular economy principles to all biological resources. CB is responsible for transforming waste and biomass into biofuels, bioplastics, and bio-based chemicals, among other value-added products. CB expands CA to the economic level, which is beyond the agricultural sector (Table 7.1).

7.2 Circular Agriculture Bioeconomy

Linear agricultural and economic systems overuse natural resources and accumulate vast amounts of by-products. A mindset shift is necessary to adopt circular agriculture and bioeconomy practices to overcome these overuse issues. Both CA and CB are integral components in responding to environmental shifts like climate change, build-up of waste, and depletion of resources. As shown in Fig. 7.1, these two concepts could be integrated into circular agriculture bioeconomy (CAB), which emphasizes the development of a renewable economy and the extension of value chains of products and resources while minimizing waste generation, enhancing food production, mitigating greenhouse gas emissions, and reducing dependence on non-renewable resources (Brandão et al., 2021). CAB is still an emerging idea for reducing and reusing resource needs, making CA economically sustainable. Its

Table 7.1 Examples of circular agriculture practices

Dutch dairy farming: Circular principles of a sustainable loop are exhibited by how the Dutch use cow manure to enrich the soil with nutrients that better equip the grass to grow and, in turn, provide the cows with feed (Lefebvre & Inbusch, 2024).
Aquaponics systems: Aquaponics is a closed-loop system that combines aquaculture and hydroponics. Waste from fish provides plants with nutrients to grow, and the plants filter and clean the water for fish (Junge et al., 2017).
Spent grains for mushroom cultivation: Spent grains from breweries are repurposed to cultivate mushrooms, which minimize waste and create new food sources (Gmoser et al., 2020).
Manure-to-biogas: Livestock manure is converted into biogas in farms through anaerobic digestion. This process produces biogas and biofertilizers, supporting the production of crops that feed livestock (Wang et al., 2021).
Black soldier Fly composting: Organic waste is composted using black soldier fly larvae. This reproduced insect is then processed into livestock feed and composted into organic fertilizer, which provides nutrients to crops whose waste is used to feed the larvae (Terrell and Ingwell, 2022).
Grape pomace utilization: Grape pomace produced from winemaking in France is turned into value-added products (biogas, compost, and feed) that minimize waste and generate new revenue streams (Wang et al., 2024).
Banana peel biofertilizer: Banana peels are fermented into biofertilizers to reduce agricultural waste and serve as a natural, low-cost alternative to synthetic fertilizers in Ecuador and India (Muniappan et al., 2023).
Seaweed cultivation for livestock feed: Fast-growing seaweed farms supply nutrient-dense animal feed in Norway and Iceland. The benefits include reducing the need for conventional grain-based feeds, absorbing excess oceanic carbon dioxide, and reducing methane emissions from cattle (Liu et al., 2025; Rajauria, 2015).
Shellfish waste as soil amendment: Discarded crab, oyster, and mussel shells are grounded into power and used as soil amendments in coastal regions since the powder is rich in calcium and micronutrients (Zhan et al., 2022).
Coffee waste bioreactors: By-products of coffee processing (e.g., coffee pulp and husk) are fermented or composted to produce biogas, animal feed, and organic fertilizer in Colombia and Brazil (Pillaca-Pullo et al., 2025). Such waste reuse creates alternative revenue streams.
Wool mulch for soil protection: Waste wool from sheep farms are used to replace plastic-based mulches in New Zealand and United Kingdom as the wool can be repurposed into biodegradable mulch that slowly releases nitrogen, retains soil moisture, and suppresses weeds (Sharma et al., 2019).

advantages need to be fully addressed to examine its economic and political feasibility in pace with technological advancement.

The benefits of adopting these sustainable practices include reducing environmental impacts by diminishing excessive waste and avoiding overexploitation of natural resources, which often occurs in traditional farming and industrial systems. The repurposed food waste and agricultural residues significantly reduce landfill

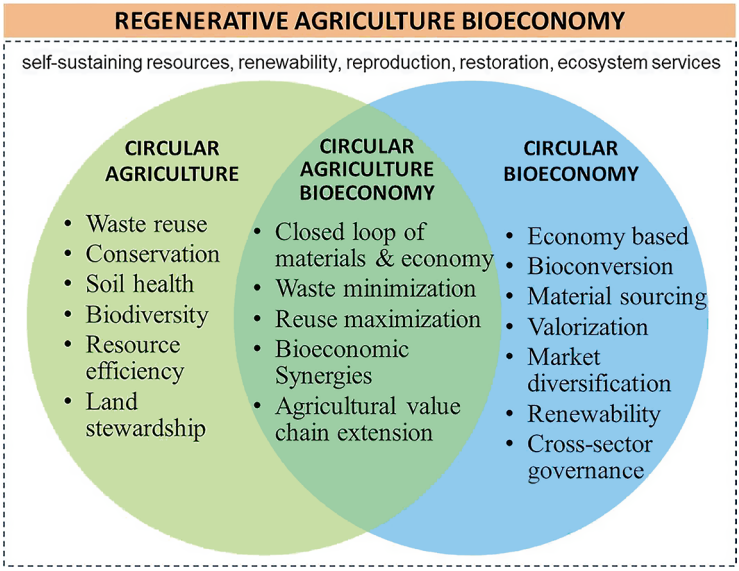

Fig. 7.1 Relations and scopes of concepts

accumulation and methane emissions, creating bio-based products such as fertilizers and biogas (Ashokkumar et al., 2022). Such development through circular practices has occurred in the renewable energy sector and bioprocessing areas (Tan & Lamers, 2021).

CAB contributes to the sustainability of environmental, economic, and social implementations. It aims to drastically reduce pollution, greenhouse gas emissions, and resource waste by aligning with global climate goals. In environmental sustainability, CAB can conserve a critical resource in regions with water shortages by facilitating the resumption of water through effective wastewater and irrigation techniques. In economic sustainability, CAB applies biotechnology to transform agricultural by-products into renewable energy and materials, which aids in reducing waste and generating new economic opportunities. For example, using animal manure for fertilizer or crop residues for energy production can reduce the demand for costly inputs. Farmers and businesses can yield additional revenue by converting previously considered wastes into new products like biofuels (Varjani et al., 2021). For example, technologies have been developed to convert concentrated sugars into chemicals with a wide range of applications, such as plastic bottle making and food wrapping (e.g., MOSAIK Technology) (Khanna et al., 2024). As a result, CAB can enhance economic stability and reduce supply chain disruptions due to decreased reliance on non-renewable inputs while boosting local production processes (Kumar Sarangi et al., 2023). In social sustainability, CAB improves food security and the creation of jobs in rural communities. International frameworks like the Paris Agreement are aligned with circular approaches because food security and job creation advantages outweigh the challenges of high start-up costs and lack of

education surrounding the necessity of CAB practices. CAB presents transformative solutions for a sustainable future by closing resource loops.

7.3 Regenerative Agriculture Bioeconomy

Circularity focuses on the extension of values of products and resources. However, circular practices are only a part of regenerative practices. Upgrading the agriculture bioeconomy from a circular to a regenerative level can ensure long-term sustainability and resilience of agriculture. Regenerative agriculture (RA) is a holistic approach for farming that helps enhance or even restore soil health, sustainably produce food, improve water cycles, sequester carbon, and increase biodiversity. Its objective is not just to sustain the current conditions of farms, but to go a step further regenerating the degraded ecosystems. Though it was coined in the 1980s by the Rodale Institute, RA has been traced back to Indigenous land stewardship practices. This traditional ecological knowledge, which emphasizes reciprocity with the land and balance in nature, has evolved through research in holistic management, agroecology, and permaculture. In today's time, RA is imperative to movements focused on climate resilience, bioeconomy, and rural revitalization.

Regenerative agriculture bioeconomy (RAB) aims to restore the environment while creating self-sustaining, closed-loop systems for supporting a long-term agricultural economy. RAB encompasses CAB (Fig. 7.1). CAB pursues a closed resource loop with resourceful usage of materials across economic, societal, environmental, and health dimensions (Fig. 7.2). In comparison, RAB emphasizes the reduction of overconsumption, restoration of the agricultural ecosystem, renewal of biological resources, and sustainability of agricultural services across the same dimensions. Both circular and regenerative practices can provide substantial

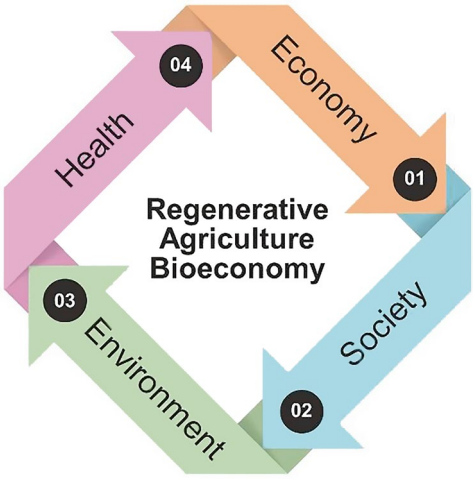

Fig. 7.2 Benefits of regenerative agriculture bioeconomy for interactive key systems

economic benefits by creating values from renewable biological resources through technological innovations and advancements.

RAB can reshape food ecosystems by converging sustainable and efficient farming technologies at a systems level. Efficient resource use and healthy and fertile soils can impact the food supply and economy through enhancing crop yields and reducing responses to environmental stressors. Regenerative systems ensure that agricultural by-products are repurposed for value-added products and ecological restoration that benefits production cycles (Schipfer et al., 2024). Precision farming and biorefineries are good examples of innovative technologies that efficiently convert resources into value-added products while minimizing detrimental impacts on the environment and enhancing productivity.

RAB practices create opportunities for sustainable livelihoods as they foster local production systems and, in turn, empower rural communities (Srivastav et al., 2025). Small-scale biogas plants and other decentralized production systems supply local communities with energy and economic benefits. As a result, communities experience improved health and cleaner environments with the introduction of better waste management and reduced chemical use in agriculture. In addition, new employment opportunities especially become available in rural communities when RAB is introduced to fields like waste management and bioenergy production (Srivastav et al., 2025).

RAB reduces resource dependency by increasing the reproduction of resources and the restoration capability of resource-producing ecosystems. These functions enhance economic stability and reduce dependence on finite resources such as fossil fuels, permitting resilience to market fluctuations and disruptions in the supply chains. Regenerative practices are critical for a sustainable and healthy future as their advantages range from economic resilience to environmental sustainability and social well-being. They pave the way for innovation and resilience by reshaping the traditional agricultural and associated industrial systems. Overall, RAB benefits long-term renewable innovation and sustainable development by integrating biological and economic cycles, which are climate positive (Table 7.2).

7.4 Circular Bioeconomy Versus Regenerative Bioeconomy

Byproduct reuse, resource efficiency, and waste reduction are principles shared between CB and regenerative bioeconomy (RB). However, they differ in scope, aim, objective, and outcomes. The scope of CB focuses on promoting sustainability through efficient resource management and designing waste out of the system while the scope of RB integrates holistic approaches and nature-based solutions to create resilient economies that work in balance with the environment going beyond sustainability. CB aims to reduce resource constraints and degradation by reusing biological resources for as long as possible, making a neutral influence on the environment. In comparison, RB goes beyond resource reuse to restore and enhance ecosystems for more alternatives and reproduction, making a positive influence on

Table 7.2 Examples of regenerative agriculture practices

Gabe Brown's regenerative farm: Cover cropping, no-till farming, and rotational grazing are practices in place to improve soil quality, crop yields, and ecosystem resilience in North Dakota, USA (Waterfield, 2020).
Sustainable rice intensification: Sustainable rice intensification manages plants, soil, nutrients, and water to increase rice yield during farming in Asia and Africa (Grecequet et al., 2024).
Holistic management: Farmland water infiltration improves land health. Soil organic matter is increased to support food quality and steward natural resources (Reeve et al., 2016).
Organic regenerative farming: Involves the employment of rotational grazing, composting, no-till practices, cover cropping, crop rotation, and no synthetic fertilizers or pesticides to rehabilitate degraded soil and reap more nutrient yields (Qamar et al., 2024).
Zero budget natural farming (ZBNF): ZBNF is a set of farming practices used in India and other countries to encourage intercropping, increase soil organic matter, and avoid using chemicals. The practices reduce water by 50% and electricity cost for all crops (Saikat, 2020).
Kiss the ground farms: Intercropping and compost applications are used on this farm in the USA to limit carbon emission and enhance soil fertility to combat climate change and feed everyone (Gunawan, 2023).
Hydraulic regenerative cultivation: This regenerative farming recycles water into agriculture areas without knowing or measuring saturated hydraulic conductivity, which is important for soil health and water management (Bilibio et al., 2025)
Silvopasture: Reliance on synthetic feeds is reduced by integrating trees, livestock, and pastures into a single system, which improves carbon sequestration, animal welfare, and soil health (Rowntree et al., 2020).
Mob grazing: Rotating livestock across dense pastures mimics natural grazing, increases soil fertility, prevents overgrazing, and reduces methane emissions (Grandin, 2022).
Integrated Rice–duck farming: Ducks are raised in rice paddies where the ducks fertilize soil with manure, eat pests and weeds, and oxygenate the water. This practice improved crop yield and biodiversity while eliminating synthetic inputs in Japan and China (Sheng et al., 2018).
Perennial grain cultivation: Growing perennial grains like Kernza (a type of perennial wheatgrass) makes crop production more resilient in the USA and Canada. They remain productive for two or more years and provide many benefits, such as reduced replanting and operational costs, less soil erosion, nutrient conservation, and carbon sequestration (Cassman & Connor, 2022).

the environment. The objective of CB is to keep materials in continuous use to minimize waste and maximize resource efficiency while the objective of RB is to improve biodiversity, replenish resources, and rebuild ecosystems to enhance and restore natural systems. The outcomes of CB are materials and products that are continuously repurposed in a closed-loop system, reducing environmental impact and the dependency on new resources while RB creates economic activities that

promote natural ecosystem functions and social well-being while producing goods and services through self-sustaining approaches. For example, silvopasture as an RB system integrates nature-based solutions to not only recycle animal waste and reduce reliance on synthetic feeds but also develop natural and social capital which ensures long-term resilience of food production. Such a regenerative approach replenishes soil health, improves water cycles, and increases carbon sequestration through means of biodiversity conservation and sustainable land management practices. The transition from CB to RB relies on the extent of using biological resources for generating more biological resources, products, and values—an amplifying effect.

7.5 Roadblocks of Regenerative Agriculture Bioeconomy

RAB has many advantages; however, there are underlying issues to resolve. Waste is continuously produced, and the quality of recycled materials decreases each time it is cycled through the closed-loop system. High start-up expenses dissuade people from following the practices. In addition to this, a general lack of knowledge on the subject forms a barrier against those wanting to pursue the objectives of RAB. Inadequate workplace training stems from this lack of knowledge, resulting in obsolete methods of RAB. Implementing RAB practices is also hindered by complicated issues regarding policies, infrastructure, and market demand. Addressing these challenges is critical to transitioning to a sustainable agricultural system like RAB.

The high start-up costs of RAB are one of the biggest challenges. The financial barriers make implementing RAB practices in rural communities challenging, especially since the infrastructure, technology, and new business models require high initial investments. Advanced processes require significant upfront investment, such as biorefineries, precision agriculture, and waste-to-energy technologies. Due to the often-required substantial investment, small and medium-sized farms find it difficult to partake in the regenerative agriculture bioeconomy. The costly infrastructure to establish biogas plants, composting facilities, and bio-based productions is necessary, but this capital expense is beyond reach for some rural community farms. The lack of incentives, grants, or subsidies challenges many farmers and small businesses in securing funding for transition to RAB. Unlike traditional linear agricultural systems, RAB solutions can take many years to become profitable. This slowness in profitability often dissuades investments due to the long payback period. Transitioning from conventional practices to circular models like CAB and regenerative models like RAB is difficult for farms and businesses based on the lack of risk-sharing mechanisms and financial assistance policies.

Another barrier to RAB is the lack of general awareness and understanding of the RAB principles. This concept is relatively new, so the farmers, businesses, and policymakers are unfamiliar with its practice and how it has potential benefits and applications. The linkage between limited public awareness, lack of educational

programs, and resistance to change all relate to challenges and uncertainties within the RAB. There is low demand for bio-based products since many consumers and businesses do not understand the concept and benefits of RAB. The knowledge gap in the regenerative economy slows the adoption of RAB practices. There is also little emphasis on the RAB principles due to traditional farming practices being passed down from generation to generation (Giurca, 2023). The traditional practices have been ingrained in the current system, and farmers are hesitant to adopt any new practices since they require a shift in operations. They know more about conventional production methods. To combat a difficult and slow transition to RAB, widespread education and awareness are necessary. Unfortunately, many academics and scholars have not even been introduced to the idea of a circular or regenerative bioeconomy due to its progressive outlook on changing energy, agriculture, and industrial sectors. Though to some, a revolutionized circular/regenerative bioeconomy may appear to help solve the energy and climate crises, many citizens and legislators alike are not convinced of its applicability yet.

The lack of knowledge leads to a lack of training and technical experts, which poses an obstacle for farmers interested in RAB strategies and practices. Many in industry do not possess the required knowledge or skills to successfully implement RAB solutions, whether from a lack of technical expertise, limited access to training programs, or slow adoption from industry leaders. Technologies that support RAB are improving rapidly. Still, RAB will remain an unrealistic ideal if the economic feasibility of the technologies is not aligned with the need for progressive changes in our energy and food sectors and if farmers and workers are not provided enough development programs or certification courses to get trained in technologies such as bioconversion and waste reuse techniques. Business owners in the agriculture sector are reluctant to invest in workforce development due to the lack of clear training guidelines or industry standards. To effectively implement RAB strategies, vocational training, curriculum, and on-site education programs are essential in expanding farmers' and workers' knowledge base and skill sets.

Current regulation frameworks and government policies are inadequate for shaping the transition to RAB based on inconsistent regulations, limited incentives, and complicated approval processes for bioeconomy (Butu & Rodino, 2025; Dürr & Sili, 2022). Many businesses and farmers often get confused by the lack of unified and structured policies that guide RAB practices. There are not enough subsidies, tax breaks, or financial incentives to sufficiently encourage investments in RAB (Wurth, 2024). These practices can be adopted based on circular initiatives requiring complex regulatory approval, like converting waste into energy. Policymakers should create clear and supportive policies ensuring safety and environmental standards are met while promoting RAB actions.

Market and infrastructure-related issues hinder the successful implementation and progress of RAB practices despite strong supply chain logistics and market demand. Limited recycling and processing facilities, fragmented supply chains, and low market demand for bio-based products are all challenges farmers and businesses face that aim to practice RAB. Most countries, including more developed ones, have a "barrier" in the infrastructure needed to introduce new energy sources

and agricultural strategies that can reduce the reliance on non-regenerative resources (Salvador et al., 2022). For example, the storage capacities for biofuels, biowaste, and the energy being produced remain a challenge that needs to be solved to advance RAB implementation. Generally, it is difficult for farmers to experience regenerative initiatives when their community lacks the necessary infrastructure to process agricultural residues and waste into bio-based products, as this can be costly for rural farmers. For these farmers, well-connected networks for collecting, processing, and redistributing biological materials are nonexistent or underdeveloped, meaning efficient RAB systems are out of reach for these communities (Bottausci et al., 2022). To establish profitable RAB markets, consumers and businesses must drop their preferred traditional, fossil fuel-based products and instead use bio-based alternatives.

Several issues must be overcome to successfully enable the widespread adoption of RAB, even though it holds great promise for being self-sustaining, resource-efficient, and system-restoring. Significant barriers of high start-up costs, lack of general knowledge, and insufficient training and regulations require niche solutions like financial incentives, educational programs, and courses, along with workforce development initiatives and training. To effectively implement RAB, policy reforms, investment into infrastructure, and stronger market demand for bio-based products are necessary (Pal et al., 2024). By overcoming these challenges and uncertainties, RAB can be implemented to enact a smart digital management system of resources, technologies, and supply and feedback networks across sectors at multiple scales.

7.6 Solutions and Opportunities

RAB highlights the integration of sustainable ecosystem services with economic innovation. It is a comprehensive approach to modern agriculture that reshapes our society from non-renewable to renewable conditions. It supports both sustainable food systems and resilient economies with self-restoration capability. This goal is achievable through practices such as value-added processing, soil health rejuvenation, limiting carbon emissions, enhanced biodiversity, and regenerative supply chains, which can be facilitated by technological innovations, policy support, and collaborative frameworks (Fig. 7.3).

Soil health improvement by reduced tillage, crop rotation, and cover crops contribute to RAB. These practices boost capacity to mitigate climate change but also enhance soil fertility and productivity. RAB practices create habitats for organisms by integrating diverse plant species and promoting biodiversity, which supports pest control, pollination, and nutrient cycling, among other ecosystem services. An example of this can be seen by farmers who integrate their cropland with prairie strips, which are strategically planted native plants in low-yield areas in efforts to address soil erosion, biodiversity loss, and nutrient pollution (Kemmerling et al., 2022). In addition, RAB can enhance agro-ecosystem services by capturing carbon in soil by applying biowaste-based fertilizers.

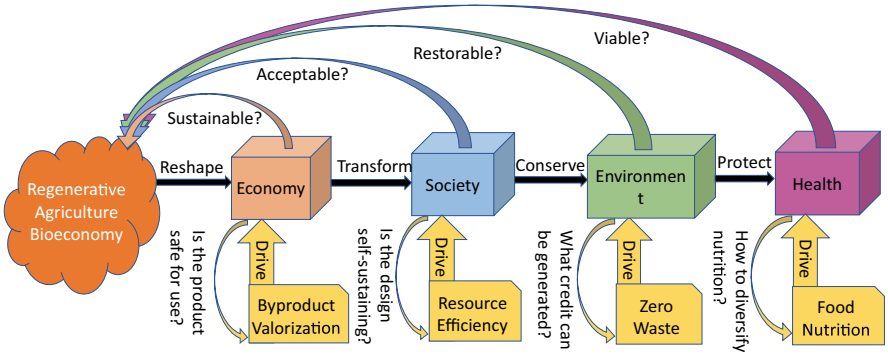

Fig. 7.3 Feedback interactions that drive regenerative agriculture bioeconomy

Reducing agricultural dependence on synthetic inputs (e.g., fertilizers, pesticides, and herbicides) through regenerative agriculture bioeconomy can increase farm profitability by lowering production costs and ensuring soil and human health. The market for sustainably produced goods permits farmers to charge premium prices. An innovative solution for cultivating sustainable agro-industries, where the forest's natural resources are valued more than logging and mining that cause deforestation, is becoming popular in the Amazon rainforest and benefits the local community bioeconomy (Garcia et al., 2004).

Technological advancements such as artificial intelligence and biotechnology are also critical in supporting RAB by providing solutions to optimize resource utilization and efficiency, improve soil health, enhance crop resilience, maximize byproduct values, and increase product yield and quality. It has been demonstrated in the World Economic Forum that artificial intelligence has the potential to create new revenue streams and facilitate the development of regenerative agriculture bioeconomy (Rowe, 2025). Another example is new genomic techniques (NGTs). NGTs (e.g., genome editing tools like CRISPR-Cas9) can be used to make targeted changes to an organism's genetic material through mutagenesis and cisgenesis. These advanced techniques allow more precise and faster alterations compared to traditional genomic or breading techniques. NGTs are increasingly used in agriculture to improve crop yield, nutritional value, and resistance to diseases and pests. As a result, such biotechnologies help reduce agricultural reliance on pesticides and fertilizers and strengthen agricultural resilience to climatic stresses, supporting the development of RAB.

RAB requires effective policy frameworks for successful implementation, including tax cuts, subsidies, education programs, and research funding. Stakeholder engagement is also critical for the success of RAB implementation. Farmers, policymakers, investors, and researchers must work together to develop holistic roadmaps that ensure effective actions to overcome barriers such as high initial cost, lack of general knowledge, and scarcity of policies. The roadmaps should include methods of training programs on regenerative agriculture, platforms specifically for sharing knowledge, and expansion of educational initiatives. Also, the roadmaps should

offer opportunities for the government to implement regulatory reforms to integrate RAB principles into sustainable agriculture frameworks.

7.7 Artificial Intelligence for Regenerative Agriculture Bioeconomy

Artificial intelligence (AI) enhances efficiency, optimizes resource use, and drives innovation in the field of circular bioeconomy. AI plays a critical role in advancing RAB by improving processes of production, recycling, manufacturing, monitoring, and business models.

- *AI-Driven Precision Agriculture*: By analyzing crop health, weather patterns, and soil data, AI enhances biomass production and sustainable farming as machine learning models are being developed to predict optimal planting times, pest control strategies, and irrigation needs which aid in enhancing yield efficiency and reducing chemical use (Ali et al., 2025).
- *Biowaste Optimization and Recycling*: AI systems can identify, sort, and process valuable bioproducts such as bioplastics, biofertilizers, and biofuels through smart waste management to optimize collection routes and maximize resource recovery (Aniza et al., 2023).
- *Biomanufacturing and Process Efficiency*: Enzyme engineering, optimizing fermentation, biotechnical advancements, and microbial processes for producing biofuels, pharmaceuticals, and bio-based chemicals are accelerated through AI. Production can be streamlined to reduce cost and waste by machine learning algorithms (Rathore et al., 2023).
- *Supply Chain Transparency and Circular Business Models*: Real-time tracking of bio-based materials and biomass is enabled by AI-powered blockchain systems enhancing circular supply chains, ensuring sustainability compliance, and reducing inefficiencies (Fernández et al., 2025).
- *Ecosystem Monitoring and Regeneration*: Regenerative initiatives are supported by carbon sequestration, monitoring soil health, and biodiversity through AI-enhanced predictive analytics and remote sensing whose insights guide conservation efforts and land-use decisions (Jahan & Islam, 2025).
- *Smart Bio-Packaging and Material Innovation*: The development of recyclable and biodegradable materials that foster a sustainable packaging industry and reduce reliance on fossil-fuel-based plastics is expedited by AI-driven research (Adeyi et al., 2025).

Through the integration of AI into circular bioeconomy, industries can reduce environmental footprints, enhance resource efficiency, and create a more resilient economic model. AI is an invaluable tool in transforming a sustainable, circular bioeconomy through its ability to predict outcomes, analyze complex systems, and optimize processes.

7.8 Conclusions

Introducing circular and regenerative strategies in the agriculture bioeconomy may seem idealistic. However, the barriers are just as glaring as the solutions themselves. The communication of circular and regenerative bioeconomy is one major setback both economically and politically. Substantial investments have been mobilized to jumpstart circular bioeconomic and agroeconomic strategies, especially within the European Union; however, initiating and conversating about such a profound transformation of current economic and agricultural strategies is difficult due to fundamental changes in policy, technologies, and practices under current restructuring of supply chain networks at regional and global levels. Communicating this innovative but complex concept remains an important challenge for policymakers, academics, and the broader public.

RAB is a transformative framework that combines economic viability with environmental sustainability. As far as sustainability is concerned, both fuels and materials derived from organic agricultural by-products can be a stepping stone to solving the ever-impending challenges of non-renewable resources globally. Using agricultural waste as a "feedstock" for producing more biological resources is a clean, eco-friendly process of manufacturing value-added chemicals, securing environmental health, and boosting the energy economy. Although investments may be initially higher for these regenerative practices, the long-term effects will be invaluable in areas where food-energy-water challenges are significant. RAB has great potential to transform agriculture into a sustainable and resilient enterprise by embracing circular and renewable practices that leverage technological innovations, restore ecosystems, and foster supportive policies. However, realizing this potential depends on how society will strategically pursue a renewable economy toward the net-zero emission goal in the coming decades.

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Chapter 8
The Bioeconomy and Historically Underserved Communities

David Zilberman, Chyi-Lyi Liang, Joseph Cooper, and Herrick Fox

8.1 Introduction

The bioeconomy will provide new sources of income for the natural resources sectors, including agriculture, forestry, and fisheries. It will rely on advanced knowledge in the life sciences and new scientific capabilities to increase the productivity of natural resources in their current production activities and to provide the capacity to steer the economy from reliance on non-renewable to renewable resources. The bioeconomy aims to address the challenges of climate change, food security, biodiversity loss, and rural development. This chapter seeks to analyze how the bioeconomy will benefit disadvantaged communities. We will investigate under what conditions it will provide new sources of jobs and income benefitting underprivileged communities and assess what policies are needed to contribute to gains of disadvantaged communities from the bioeconomy.

To answer these questions, we will first identify the different elements of the bioeconomy, identify how the evolution of the bioeconomy will be affected by

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climate change, and then specify the disadvantaged communities that may be targeted by policies to gain from the bioeconomy. Building on this foundation, we will analyze what elements of the bioeconomy may benefit different populations and what policies may lead to increased gains.

8.2 USDA's Bioeconomy Enterprise

In many respects, the US Department of Agriculture has served the nation's bioeconomy since its founding in 1862. Numerous programs throughout the Department support biomass supply, bioenergy, biobased product manufacturing, and bioengineering, as well as the farms, forests, waste streams, infrastructure, and technologies employed to deliver them. USDA's role in developing the bioeconomy is a coordinated effort across research and development, significant investments in capacity building, and market development for the countless goods and services that the bioeconomy delivers. In each respect, the bioeconomy can drive increased equity and resilience in communities, landscapes, and economies across the USA and around the globe.

In recent years, USDA's bioeconomy enterprise has been an integral part of the Department's strategy for finding new ways to support smaller farms and underserved communities amid the increasing consolidation seen in American agriculture. In 2022, farms greater than 5000 acres in size comprised 2% of U.S. farms and controlled 42% of all farmland, while those fewer than 50 acres comprised 42% of U.S. farms while controlling 2% of all farmland.

USDA's strategy for promoting a robust and resilient bioeconomy, as outlined in its 2024 Biomass Supply Plan and Implementation Framework, sets forth actions to support smaller and less-capitalized farms by creating revenue opportunities in new feedstock commodities from rotational crops, animal waste, and non-sawlog woody material. It also seeks to reduce the cost and volatility of inputs such as fertilizer by promoting the delivery of lower-cost biobased products that are produced locally.

This strategy also outlines actions that support rural and underserved communities by promoting investment in processing infrastructure closer to the biomass supply, creating more jobs and economic activity. These actions also promote the resilience of this economic activity and the landscapes that support it by creating market opportunities leading to improved soil health and reduced risk of catastrophic wildfire.

8.3 The Different Segments of the Bioeconomy

The bioeconomy contains multiple segments, each relying on specific feedstocks as inputs to produce outputs that can be goods or services (Zilbeman et al., 2025). The green bioeconomy includes agriculture and forestry. The blue bioeconomy is

aquaculture and fisheries. The brown bioeconomy is recycling and reusing. The white bioeconomy is biomanufacturing. Lastly, the microbial bioeconomy utilizes microbial elements. All of the bioeconomy components fit into the goal of enhancing sustainability and achieving a Circular Bioeconomy, which will minimize the amount of unutilized residues and negative externalities (Khanna et al., 2024).

The first segment is the Green bioeconomy. The green bioeconomy, including agriculture and forestry, may produce plants or other living organisms to produce feedstock for energy and chemical production, sequester carbon, and produce services such as tourism. As recent European studies suggest, the green bioeconomy is the largest sector of the bioeconomy (Wesseler & von Braun, 2017). A key element that will enhance the development of the green bioeconomy is the development of integrated breeding systems for plants, animals, and other organisms that will take advantage of new knowledge on multiple and evolving tools of biotechnology and will address challenges of food security, climate change, and the preservation of biodiversity.[1] Furthermore, the green bioeconomy will require improved agricultural practices to enhance precision and expand supply chains. Transitioning from a fossil fuel-based economy to renewable biomass requires significant expansion of supply chains and the capacity to process the feedstock, convert them to useful products, and transfer and use them across locations. It will enhance logistical challenges but provide new income sources to the rural community, provide avenues to sequester carbon, and address the challenges of climate change.[2]

The second segment is the Blue bioeconomy, which relies on bodies of water, including lakes, rivers, and oceans. It may utilize fish, seafood, and algae. The Blue bioeconomy may be crucial for sequestering carbon. Fisheries and aquaculture are the primary protein sources, but these products produce significant externalities from producing fishmeal and overfishing. Identifying and developing new carbon sources for human and animal feed is a major challenge, and algae can be a significant source. Furthermore, the sustainable development of cheap proteins from multiple sources will be crucial for replacing fishmeal as a food source for aquaculture and reducing the loss of marine biodiversity.[3]

The third segment is the Brown bioeconomy, which utilizes reusable and recycled waste materials to create new products and reduce pollution. It is a key part of the circular economy, which aims to create a more sustainable economic system. Some common elements of the Brown bioeconomy are **insects (e.g., vermicompost), animal waste (e.g.,** methane for a source of fuel), **tree waste (e.g.,** biochar

[1] https://firebasestorage.googleapis.com/v0/b/kistorm-media.appspot.com/o/CASA-Bio%20Docs%2FAgSystems%20Accelerated%20Breeding%20for%20a%20Resilient%20Bioeconomy.pdf?alt=media&token=36926471-a7ca-4f1b-8398-9c955dfe4a28

[2] https://firebasestorage.googleapis.com/v0/b/kistorm-media.appspot.com/o/CASA-Bio%20Docs%2FBuilding%20Resilient%20Biomass%20Supply%20Chains%20for%20a%20Sustainable%20Bioeconomy.pdf?alt=media&token=bc9f9a53-567c-41d1-a7c1-003d5ae56583

[3] https://firebasestorage.googleapis.com/v0/b/kistorm-media.appspot.com/o/CASA-Bio%20Docs%2FDiversifying%20Edible%20Protein%20Sources%20for%20a%20Sustainable%20Future.pdf?alt=media&token=7b6be9eb-4779-455b-bfb0-7294165cb8b1

for soil amendment), **metals, plastics, fertilizers, and clothes (e.g., recycled fabric and home goods).** The brown bioeconomy aims to use waste products as feedstock to recycle and reuse materials that have already been inputs for production activities. Waste carbon from agriculture and industry and consumer waste can be transformed into critical minerals, food, and fuel while providing new sources of income and reducing or eliminating externalities.[4]

The fourth segment is the White bioeconomy, consisting of biomanufacturing (e.g., created in labs, greenhouses, and factories), where living systems are crucial in producing new products. That includes biomanufacturing medicine through genetic engineering or other utilization of living organisms and genetic material. Developing new mechanisms to produce and deliver vaccines, other medicines, food additives, and other products from various living organisms through modification of organisms can provide new sources of income and increase the availability of valuable treatments.[5]

Finally, the microbial bioeconomy relies on very small organisms, frequently manipulated using advanced molecular and cell biology technologies to benefit humans and provide value-added in agriculture or health. Biological technologies can be utilized to capture carbon and store it in an environmentally sustainable and economical way. In some cases, carbon capture biological agents can lead to the development of new products that can be used for food, energy, and other economic activities.[6] Another two segments of the bioeconomy are the recreation bioeconomy, which includes a wide array of nature recreation activities, and the gastronomy bioeconomy, which involves food preparation and service.

8.4 Climate Change and the Bioeconomy

Crisis provides opportunities for change, and climate change control is a major reason for establishing a bioeconomy. But, climate change will affect how the bioeconomy will be developed. Adaptation to climate change may spur developments in the bioeconomy, and the bioeconomy will provide mechanisms for mitigation and resilience. Climate change is likely to result in migration of climatic conditions where conditions occurring closer to the equator will move closer to the poles. For example, the climate of Southern California may move to Central California. While

[4] https://firebasestorage.googleapis.com/v0/b/kistorm-media.appspot.com/o/CASA-Bio%20Docs%2FCreating%20Value%20from%20Waste%20Carbon%20for%20a%20Circular%20Bioeconomy.pdf?alt=media&token=0093f104-92ab-4ade-8071-f56fa16c3d77

[5] https://firebasestorage.googleapis.com/v0/b/kistorm-media.appspot.com/o/CASA-Bio%20Docs%2FDelivery%20on%20Target%20-%20Transforming%20Vaccines%20and%20Biologics%20Delivery.pdf?alt=media&token=76837d07-6881-4979-b7e6-77b98d370674

[6] https://firebasestorage.googleapis.com/v0/b/kistorm-media.appspot.com/o/CASA-Bio%20Docs%2FUnleashing%20the%20Power%20of%20Biology%20for%20Carbon%20Capture%20and%20Utilization.pdf?alt=media&token=148d8986-2418-4532-92df-0840feea2319

warmer conditions may limit production opportunities in Oklahoma, they will expand the conditions in Montana and Wyoming (Zilberman et al., 2002). We have already seen significant crop movement among farm regions (Fei & McCarl, 2023). The movement of agricultural production from one area to another will provide opportunities for populations not involved in agricultural activities to get engaged, especially if they get the training and resources, although others might lose their current opportunities in agricultural activities. We expect that new opportunities will come up in states like North Carolina, Oregon, and others as their temperatures get warmer, and that may provide opportunities to historically disadvantaged communities. Another impact of climate change is the higher likelihood and severity of extreme events, which increase the vulnerability of food systems, require investment in resilience, and suggest a need to increase redundancy of food production to diverse nutrition and supplies, which again provides new employment opportunities. One question is to what extent increasing redundancy increases food costs on average—there may be a redundancy–efficiency trade-off. A third impact of climate change is increased snowmelt and a higher likelihood of floods, and there will be a need to develop new sources of water storage to replace snowpack. Finally, climate change will result in rising water levels and may lead to evacuation of coastal areas and migration to inland locations. These changes will increase the burden on agriculture and challenge it to be more productive but also provide new opportunities for employment and careers in areas without traditional agricultural activities.

The bioeconomy introduces new opportunities and challenges by establishing new supply chains and industries and may lead to many new activities in rural communities. The question is, where will disadvantaged communities fit in this new reality?

8.5 On Different Segments of the Underserved Communities

The USDA distinguishes between different categories of historically underserved Communities.[7] One category is *socially disadvantaged farmers and ranchers*: members of populations subject to racial or ethnic prejudice. They include Black and African American farmers, Native Americans and Alaskans, Latinx (Hispanic, Latino, or Spanish origin), Asians, and Pacific Islanders**.** Only 1.3% of farm producers self-identified as Black or African American in the 2017 census and concentrated in the Southern and Northeast states. Based on a 2018–2020 survey, African American farmers and ranchers tend to be 5 years older than other farmers (average age 65), their average farm acreage is significantly smaller (109 acres vs. 408), their average annual net farm income is $1500 compared to $37,175, their average yearly off-farm income is smaller ($66,393 vs. $97,796), and they are less likely to adopt

[7] See https://www.ers.usda.gov/topics/farm-economy/socially-disadvantaged-beginning-limited-resource-and-female-farmers-and-ranchers/ updated Monday, January 29, 2024

advanced technologies and management practices (Collins et al., 2024). Individuals of Latinx origin comprise 3.3% of all producers; they are concentrated in California, other western states, and Florida. They controlled 21 million acres in 2019, and the average annual sale of a farm was $128,358.[8]

Another group of historically disadvantaged communities includes Asians, mainly living in the West, who comprise 0.7% of farms,[9] and many of their operators in producing fruit and vegetables are well-to-do. Additionally, about 2.7% of US Farms in 2017 identified as Native American, Alaskan, Hawaiian, or Pacific Islanders. American Indian or Alaska Native producers were younger and more likely to be female than U.S. producers overall. Their farms accounted for less than 1% of U.S. agriculture sales and more than 6% of U.S. farmland. Seventy percent of the farms specialize in livestock and dairy, only 3% grow field crops, and 22% grow specialty crops (fruits, vegetables) and other crops.[10]

When the distribution of crop farm operators is examined by sales class, Black farmers have their highest share of operations in the lowest sales classes ($1000–$9999 in annual sales).[11] In contrast, the distribution of operations with white producers is skewed relatively more to the higher sales classes, but the percentage of Asian producers in the highest sales class ($1000,000 or more annually)[12] is higher than the percent of White producers in that class and Hispanics slightly higher. Note however that race and ethnicity shares are not uniform across commodities. For instance, non-Hispanic Black farms are more likely to specialize in cattle production (Whitt et al., 2023).

8.6 Percent of Crop Operations by Race or Ethnicity in each Sales Class

Underrepresented groups play a major role as employees in the food system. About 78% of agricultural food workers self-identify as Hispanic, as do 48% of animal-slaughtering workers, 43% of restaurant employees, 26% of all food service workers, and about 30% of domestic workers.[12] In addition, about 12% of food service workers and employees are Black, and 7% are Asian.[13] At the same time, 45% of the

[8] According to https://agamerica.com/blog/celebrating-hispanics-in-agriculture/#:~:text=According%20to%20the%20United%20States,21%20million%20acres%20of%20farmland

[9] https://www.nass.usda.gov/Publications/Highlights/2019/2017Census_Asian_Producers.pdf

[10] https://www.nass.usda.gov/Publications/Highlights/2019/2017Census_AmericanIndianAlaskaNative_Producers.pdf

[11] https://www.nass.usda.gov/Publications/Todays_Reports/reports/fnlo0222.pdf

[12] https://hispanicexecutive.com/editors-letter-latino-food-systems/#:~:text=Among%20US%20agricultural%20workers%2C%2078,National%20Restaurant%20Association%2C%202020).

[13] https://restaurant.org/getmedia/6f8b55ed-5b3f-40f5-ad04-709ff7ff9f0f/nra-data-brief-restaurant-employee-demographics.pdf#:~:text=Race%20and%20Ethnicity,-•&text=26%25%20of%20restaurant%20and%20foodservice,in%20the%20overall%20U.S.%20workforce

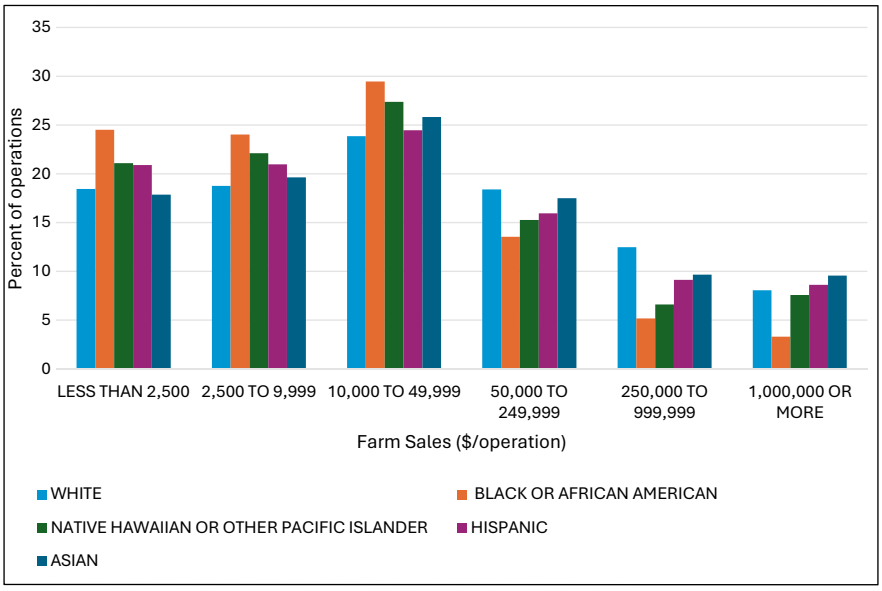

Fig. 8.1 Source: 2022 Agricultural Census, USDA. Note: Except for Hispanic ethnicity, each race category includes that race alone or in combination with other races

managers are minorities, which means that restaurants and food services employ minorities than any other sector.

Many of the food system employees are immigrants. While only 14% of the commercial fishing workforce is foreign-born, 35% of the seafood-processing industry is foreign-born.[14] In addition to farming crops and livestock, Native Americans have significant fishery and game industries that follow both traditional and modern practices. These activities are exempt from U.S. income tax and are major contributors to tribes' economic well-being.[15] The forest products industry employs 950,000 people, with many workers from disadvantaged demographics.[16]

The second category of disadvantaged communities is *limited-resource farm households* defined by low farm sales ($180,300 in 2020) or being of low-income status for two consecutive years.[17] About 9% of the farms are operated by limited-resource farmers who lost money farming. Farming households defined as limited-resource tend to be older than the rest of the farm population (average age 67 vs. 59)

[14] https://www.newamericaneconomy.org/research/sea-to-table-the-role-of-foreign-born-workers-in-seafood-processing-industry/

[15] https://nafws.org/about/background/

[16] https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://datausa.io/profile/soc/forest-conservation-workers&ved=2ahUKEwjc4YPjlrWJAxUgJUQIHf33DFEQ-tANegQIERAF&usg=AOvVaw2TysP95Az0Zp_no8KhnO4X

[17] https://www.ers.usda.gov/topics/farm-economy/socially-disadvantaged-beginning-limited-resource-and-female-farmers-and-ranchers/

and are likely to lose money farming. Their total household income, including off-farm income, is about $16,000, but their net worth is about $800,000, representing their 186 operated acres. Limited resource farms specialized in livestock and other feedstocks other than the main commodities.[18]

The third major category is *beginning farmers and ranchers*, who have 10 years of experience or less in agriculture. This group includes 17% of the two million family farms in America. This group tends to be younger than the established farm operators; 36% have college degrees (compared to 27% of operators of established farms), and households earn more than established farm households from off-farm activities.

The fourth category is *female farmers and ranchers*. Female principal operators accounted for 13% of farm households (twice as many contribute as second or third operators). Female principal operators are older than their male counterparts and are overrepresented among limited-resource farmers (27%) and beginning farms (19%).

8.7 The Likely Sources of Gains for Disadvantaged Communities from the Bioeconomy

The multiple dimensions of the bioeconomy may offer new opportunities to members of disadvantaged communities. We would analyze how different segments of the underprivileged communities can take advantage of other opportunities in the bioeconomy.

8.7.1 Opportunities in the Green Bioeconomy

The "green bioeconomy" includes multiple segments. Regarding crop production, there are major agricultural commodities in the Midwest and specialty crops along the coasts of the United States. There is a relatively low concentration of members of the underrepresented minorities in producing major commodities like wheat, corn, and soybean. While efforts could be made to enhance disadvantaged communities' access to the major agricultural commodity systems, these activities will be unlikely provide major opportunities under the current market structure. Production of field crops is capital intensive, does not provide many new opportunities for labor, and may require relocation that may not be attractive. Even with climate change and the relocation of major commodities (for example, soybeans to northern regions), the relocations will not likely be to regions with high concentrations of members of disadvantaged communities.

[18] https://www.migrationpolicy.org/content/essential-role-immigrants-us-food-supply-chain

On the other hand, members of disadvantaged communities can benefit from building a more robust bioeconomy associated with producing specialty crops and forestry in coastal states like California, Florida, Washington State, and North Carolina. Already, some of these communities specialize in producing specialty crops. For example, in a survey of about 100 farmers from minority backgrounds in North Carolina (mostly Black), we found that they use their land to produce specialty crops to specialize in the market using wind tunnels and drip irrigation and benefit from the high price provided for these crops. These farmers were part-time farmers and had specific knowledge of producing these crops and benefitted from extension service. But, selling to restaurants, farmers markets, and selective markets allows them to make a decent living. Interestingly, different members identified different niches they could take advantage of, and even the limitations of acreage to below 100 acres did not prevent them from being economically viable, but these farmers were not dependent on agriculture for their major source of income. There is more scope to engage in high-value specialty crops. When new crops are introduced or expanded, like strawberries in this century, underrepresented groups will be given access to contribute to the process.

Latinx individuals are very prominent in Florida and California's big agricultural and agribusiness complexes. As these agribusinesses expand, these groups should and are likely to benefit from the expansion. These areas will also provide the skills and leadership needed to move beyond the production of traditional fruits and vegetables to other components of the bioeconomy. Vertical farming may be a significant element of the green bioeconomy, producing high-value crops in urban setups in capital-intensive situations. It may provide new opportunities to individuals from disadvantaged backgrounds. It will require training but may lead to new opportunities. Young farmers may also be involved in the production of specialty crops, organic, and new crops, including high-value industrial crops. Entering some of these activities requires specific knowledge and education; thus, small farmers with some resources and human capital can enter into new activities. The green bioeconomy also includes forestry. Trees sequester carbon and once the incentives for sequestration become more attractive, the forestry sector will expand and produce some wood for fuel and, eventually, lumber and timber for construction. Members of disadvantaged communities are not highly represented in the forest sector but may benefit from engagement in the industry once it grows.

8.7.2 Opportunities in the Blue Bioeconomy

The USA does not have a very large fishery sector relative to the size of the economy and is an exporter of fish and seafood.[19] Fisheries are concentrated in a few

[19] https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=108472#:~:text=Consumer%20demand%20for%20seafood%20in,Service%20topic%20page%20on%20aquaculture.

states (Washington, Alaska, Maine, Massachusetts, and Texas, and there is a significant aquaculture in the Southeast). Native Americans can be major contributors to the blue bioeconomy. Acknowledging their knowledge building upon generations of knowledge of natural system functioning will enhance fisheries productivity and sustainability (Anderson, 2005). Native Americans may also use opportunities on reservations to produce new crops and other resources that exploit their availability. However, a key development is new knowledge and incorporating modern with Native knowledge for individuals who can become crucial participants in the bioeconomy. More extensive production and processing of algae as a source of fine chemicals, nutrients, and energy will provide employment opportunities for disadvantaged communities. It will include a low-paying job as laborers but higher-paying jobs for people with professional training. Suppose the industry is developing in an area with significant numbers of members of disadvantaged communities. In that case, developing training and preparation for the jobs can help build the industry and improve the individual situation.

8.7.3 Opportunities in the Brown Bioeconomy

The brown bioeconomy can be an essential source of employment for members of disadvantaged communities because recycling and reusing products can potentially be done effectively on a relatively small scale (e.g., at the farm level or the household level). For example, on-farm compost in different forms (e.g., weed, grass, crop residuals) could reduce waste, reduce expenses associated with commercial fertilizer/soil amendment, enhance soil nutrient/fertility, and improve crop yield and overall ecosystem health. Farmers living in limited-resourced areas could apply compost strategies to achieve better income (some farmers could probably sell compost to gardeners and households for gardening). Farmers could also collaborate with local schools, hospitals, restaurants, or other institutions to jointly implement compost approaches to turn "trash to treasure" and achieve the community sustainability goal in the long term (Chancey, 2021; Schwarz et al., 2022). With new activities and business development, there will be opportunities to develop employment and job-training opportunities or even start firms that can be part of the supply chains that utilize waste residue products to produce protein and other products with insects or collect wood to make biochar (Velenturf & Jopson, 2019). Increased penalties for waste and the development of technologies for reuse and recycling will provide many products for which production will need workers. Many of these opportunities will be in urban settings with highly disadvantaged growth. However, entering these industries will require training, and building small businesses will need finance. Here, joint public–private resources can collaborate to develop the training, skills, and financial resources to provide opportunities. Land-grant colleges should emphasize research on circular technologies and practices, identifying waste products, and discovering alternative ways to utilize them. Extension and universities should develop training and provide the information that would allow individuals to enter these new business fields.

8.7.4 *Opportunities in the White and Other Segments of the Bioeconomy*

As knowledge and technology improve, the range of products produced by the white and the micro bioeconomies—including pharmaceuticals and other chemicals—will expand and provide new employment opportunities. A recent white paper identified the ten existing clusters of biomanufacturing and they include the San Francisco Bay Area, Boston/Cambridge, Maryland, Virginia, Washington D.C., New York/ New Jersey, Los Angeles, North Carolina (The Research Triangle), Seattle, and the Chicago area.[20] As we can see, the clusters are located in areas close to leading research institutes. However, as the industry expands, it may establish production facilities in rural areas with appropriate human resources and locational advantages. For example, regions of North Carolina, California near Davis and part of the Central Valley, areas near Chicago, and Gainesville in Florida may develop employment opportunities in the white bioeconomy. Providing members of disadvantaged communities opportunities in these new areas may require providing training in these fields, as well as access to sources of opportunity. For example, some of the Historically Black Colleges and Universities (HBCUs) should develop training and educational foundations to enter these areas, and develop outreach opportunities to enhance access to jobs. These new sectors will have many positions requiring different levels of training, and members of underrepresented communities entering these fields may advance through learning by doing and through lifelong learning.

8.8 Challenges and Barriers for Socially Disadvantaged Communities to Engage in Bioeconomy Development

Compared with the large commercial agricultural producers, small and socially disadvantaged producers have limited resources to achieve the bioeconomy goals. The required investment and infrastructure establishment for many types of bioeconomy activities could require significant financial support. Small and socially disadvantaged producers often have challenges applying for and inquiring about loans and credits from commercial banks. Low credit scores and unstable cash income from agricultural operations become problematic. Some USDA-funded studies discussed higher risks associated with socially disadvantaged farmers (e.g., Whitt et al., 2023). Based on the survey of about 19,000 farm operators for the USDA's report, the results revealed that 64%–74% of the socially disadvantaged producers had profit margins of less than 10%, which could be an issue when it comes to crop insurance being affordable and in making successful loan applications. The survey results also showed that Black farm operators had the lowest average loan amount and received

[20] https://www.genengnews.com/a-lists/top-10-u-s-biopharma-clusters-10/

smaller government payments compared with White agricultural operators. Such financial discrepancies could trigger lower incentives or the ability to acquire investment in designing, creating, and implementing necessary technologies to participate in bioeconomy activities. Farmers earning low profit margins also seem to have less incentive to go to a Farm Service Agency or Natural Resource Conservation Service field office because they are less likely to fulfill the requirements with income levels, acreages, comprehensive financial records, or other pre-requisite components.

Lack of access to information has been a well-documented barrier for small and socially disadvantaged producers/communities to recognize and explore opportunities to enhance rural prosperity. Information is a key factor regarding technology development, innovation, and entrepreneurship. People with access to modern information and research updates are more likely to participate and engage in new economic activities. Research has shown that socially disadvantaged producers and limited-resourced communities often lack access to information due to (1) ineffective broadband and Internet systems in rural areas, (2) more difficulty harnessing research organizations or higher education institutions for support, (3) having relatively long-traveling distance to engage in in-person interactions with local agencies for services and consultation, and (4) insufficient outreach by the government to these producers in terms of access to Internet and education and other distance-related challenges, meaning that they are less likely to know what should know to prosper economically.

Trust issues have been a challenge for many small and socially disadvantaged producers to work with government agencies (e.g., https://capitalbnews.org/black-farmer-agriculture-census/). There is a long history of evidence that socially disadvantaged communities have low trust in government agencies, policies, initiatives, or programs (Burchard et al., 2015).[21] Many producers from underrepresented groups have experienced historical discrimination and oppression. Although the bioeconomy seems to create positive impacts from social, economic, and environmental aspects, producers and communities could interpret this movement as another "showpiece" from the politicians and wonder what the "catches" would be for people to participate.

Rural and urban producers and communities could hold very different perceptions regarding bioeconomy. Agricultural wastes are largely generated in rural areas, as are those from food processing, while most urban communities create more waste from consuming prepared food, clothes, and paper products. Socially disadvantaged communities in rural and urban areas face different challenges in participating in the bioeconomy's development. For example, land use restrictions such as zoning in various urban cities and counties might hinder the construction of biomanufacturing facilities. However, in some cases, less strict results in areas with minority populations may attract some of the industry, but then will generate negative externalities. The permits and environmental compliance of disposal and processing of

[21] https://www.oecd.org/en/topics/sub-issues/trust-in-government.html; https://pmc.ncbi.nlm.nih.gov/articles/PMC7988507/

biodegradable wastes could trigger debates among communities due to smell, water runoff, and other by-product-waste treatment. Each state and city in the USA has various rules to regulate, which could be cumbersome for producers to understand, interpret, and follow without facing penalties for violations.

Importance of Training, Education, and Communication of Next-Generation Workforce As we have seen, there are growing opportunities for agri-manufacturing and other elements of the bioeconomy, and they require increased knowledge and skills in biological and natural sciences. Children in disadvantaged communities may need more access to nature and agricultural and scientific knowledge to qualify for bioeconomy journals. Therefore, it is essential to generate awareness of the importance of knowledge in the natural sciences, increased access to nature, and improved skills that will prepare one's skills in the bioeconomy. Skills can improve with more access to science education and more hands-on training with equipment that can be accomplished through public/private collaboration. While there is a need to establish a general curriculum of basic training for the bioeconomy, the training at different locations should fit according to the bioeconomy at this location.

Some of the young farmers and educated individuals from affluent segments of society may contribute and benefit from the bioeconomy, and without equipping members of disadvantaged communities with the skills for the bioeconomy, they may lose from its introduction. However, with the appropriate training and support, the bioeconomy may provide ample opportunities to reduce the distributional gap in the economy.

8.9 A Global Perspective

The analysis thus far emphasizes the future of the bioeconomy in the United States, but our perspectives can be generalized. The circular bioeconomy is likely to spread worldwide and provide a substitution for non-renewable resources and control for multiple pollution problems. In most places, it would rely on interactions between universities, industry, and government, leading to technologies, infrastructure, investment, jobs, and products. In some countries, like Brazil, endowed with unique natural resources and a background in producing major commodities and converting them to bioproducts, the bioeconomy is already quite big (Valli et al., 2018). It will grow in other developing countries, but in all cases, it will remind investments in research, development, and establishment of new industries and supply chains. To share the gains from this industry more equally, it will be important to develop training and skills that allow members of disadvantaged communities to benefit from the bioeconomy.

Expanding the Consultative Group on International Agricultural Research (CGIAR) center to include research and extensions of training and development of agricultural universities and research institutes will help introduce and, most importantly, advance the bioeconomy in developing countries and may provide

opportunities to the poor. Since many bioeconomy industries are providing environmental amenities, including carbon sequestration, significant pricing will provide a major input to their position.

8.10 Conclusion

The development of the bioeconomy will require significant multidisciplinary collaboration, leading to drastic changes in several segments of the economy, including the energy sector, construction, agriculture, and food production. The new bioeconomy may combine new biological capabilities with knowledge in other fields, with the development of new materials chemically and new capabilities in artificial intelligence. The new bioeconomy would be developed during a period of climate change. Thus, the climatic conditions will affect the evolution of the bioeconomy.

The circular bioeconomy has multiple manifestations and provides a wide array of opportunities to members of different disadvantaged communities. Yet, as the bioeconomy is in its infancy, there is a need to continue research to provide the knowledge base for the bioeconomy. We need to build the incentives and other resources to support the establishment of the bioeconomy sector, and there is a need for education efforts that enable members of disadvantaged communities to gain skills and take advantage of them as employees and entrepreneurs of the bioeconomy.

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Chapter 9
The Circular Bioeconomy: Concepts, Opportunities, and Limitations

Tunç Durmaz

9.1 Introduction

Amid crises such as climate change, biodiversity loss, and resource scarcity, the traditional "take-make-dispose" linear economy has proven increasingly inadequate. In response, the Circular Bioeconomy (CB) has emerged as a crucial model to address the urgent economic and environmental challenges of our time.

CB proposes a transformative shift by establishing closed-loop systems. In this model, biological resources are not only utilized and regenerated but also returned to productive use, thereby minimizing waste and environmental damages. As ecosystems and economies grow more interdependent, CB's emphasis on sustainability, systemic integration, and resilience addresses the need for a model that can deliver greater economic prosperity and a better environment.

The necessity of CB also becomes evident when we consider the escalating competition for land, water, and other natural resources. The increasing pressure on agricultural systems to produce food, energy, and industrial materials simultaneously has highlighted the limits of traditional approaches. CB offers a way to harmonize these competing demands while increasing productivity and ecological health, through practices such as cascading resource flows and regenerative agriculture techniques. It aims not only to minimize environmental damage but also to actively restore and enhance natural systems.

In this chapter, we evaluate the opportunities and limitations of CB by focusing on market trends, economics, and policy and regulatory environments. This blend allows for a comprehensive evaluation of CB, situating it not just as an alternative economic model, but as a transformative vision capable of addressing the intertwined crises of sustainability, resource management, and social resilience. Through

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this approach, we aim to articulate under what conditions CB can realistically transition from theory to practice, fostering an economy that is circular, bio-based, and fundamentally regenerative.

The organization of the sections is as follows. Section 9.2 provides the fundamental concepts and the core principles of CB. Section 9.3 delves into the opportunities and limitations of CB, exploring how this model can drive innovation and sustainability. This section also highlights key challenges such as high capital costs, policy inconsistencies, technological gaps, and competition for land, which must be overcome to advance the CB. Section 9.4 examines the competitiveness of bio--based products and explores the role of economic metrics in evaluating their economic viability. Finally, Sect. 9.5 synthesizes these findings and consider their implications for the broader economic transition.

9.2 Fundamental Concepts and Core Principles

The transition to CB is based on core concepts that integrate circularity with bio--based systems to create a sustainable economic model. This section outlines these core principles, highlighting how CB aims to move from traditional linear production to a regenerative, resource-efficient approach.

9.2.1 Defining the CB

The CB represents significant progress in economic thinking because of the integration of circularity principles with sustainable bio-based production systems. Unlike traditional linear models, which follow a path of i) extraction, ii) production, iii) consumption, and iv) disposal, the CB seeks to create closed-loop systems where biological resources are utilized, regenerated, and continuously cycled back into the economy to the greatest extent possible.

Therefore, the CB places a strong emphasis on sustainable use of renewable biological resources, such as biomass, for producing food, products, and energy while reducing environmental impact and resource depletion. Specifically, this approach prioritizes efficient resource use and waste minimization through cascading and recycling strategies. It also promotes regenerative practices in agriculture, not only to produce goods but also to restore soil health, enhance biodiversity, and ensure long-term productivity.

Figure 9.1 offers a schematic overview of the bio-based circular carbon economy, with a focus on the role of biomass-derived carbon cycling. At its core lies a biorefinery that converts biomass into biofuels, chemicals, and materials, while also producing fertilizers for agriculture. Specifically, in this process, the CO2 captured by plants through photosynthesis is either reused in industrial operations, converted into biofuels, such as synthetic aviation fuel (SAF), or returned to the soil as

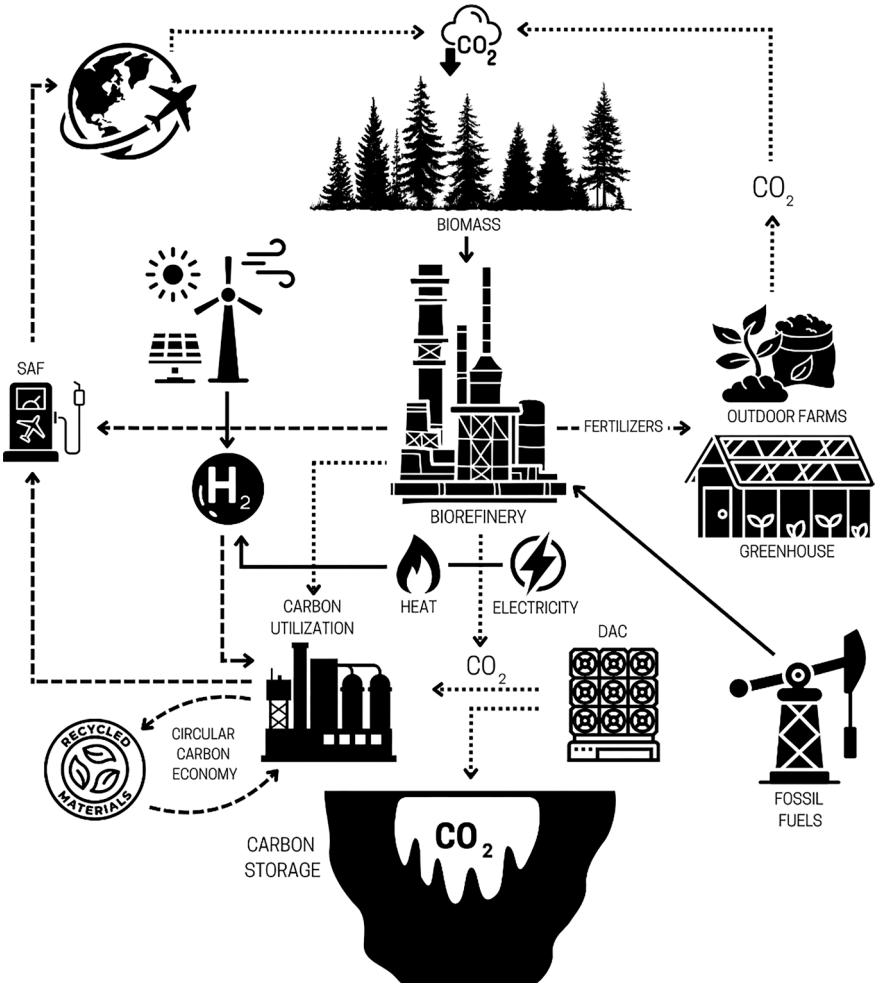

Fig. 9.1 A schematic view of the bio-based circular carbon economy. This system brings together biomass, industrial processes, and renewable energy to lower emissions, improve resource efficiency, and promote a low-carbon economy. Dotted arrows (⋯) illustrate the path of CO2, encompassing emissions, capture, and storage, while dashed arrows (– – –) highlight processed product flows, including SAF, fertilizers, and recycled materials. Solid arrows trace material, fuel, and energy flows, covering everything from biomass and fossil fuels to renewable inputs

fertilizer, thereby keeping carbon in a circular loop. Renewable energy sources like wind and solar further support hydrogen (H2) production and carbon utilization, reducing the need for fossil fuels. Additionally, Direct Air Capture (DAC) technology removes CO2 directly from the atmosphere for subsequent use or permanent storage in geological formations. Overall, the system is designed to retain as much carbon as possible within the economy, minimizing CO2 releases while aligning industrial activities with climate goals. The integration of biomass, industrial

conversion, and renewable energy in this circular approach lowers emissions, improves resource efficiency and climate action, increases economic resilience, and promotes a low-carbon economy.

The core principles guiding CB emerge from the fundamental need to create a sustainable and resilient economic system that is rooted in natural cycles and processes. These principles, as illustrated in Fig. 9.2, provide a framework for designing and implementing bio-based production systems that can regenerate resources, optimize resource use, and integrate across multiple disciplines.

The first principle is circular resource flows, which emphasize the importance of continuously regenerating resources through biological cycles, thereby maintaining ecological balance. This involves creating cascading systems where resources are reused in multiple stages, such as turning agricultural residues into bioplastics, fertilizers, and bioenergy, maximizing their value before reaching the end of their lifecycle. In sectors like forestry, this approach ensures that wood is first utilized for high-value products like furniture, later repurposed for construction, and finally used as biomass energy (UNECE/FAO, 2023; SEI, 2022).

The second principle, regenerative design, focuses on restoring, renewing, and revitalizing natural systems, thereby going beyond conventional sustainability approaches that merely aim to do no harm. Regenerative practices, such as agroforestry and cover cropping, not only produce crops but also rebuild soil health, improve water retention, enhance biodiversity, and sequester carbon. This approach ensures that economic activity actively contributes to ecosystem resilience and long-term productivity, reducing the need for external inputs over time (UNECE and FAO, 2023; European Circular Economy Stakeholder Platform, 2022).

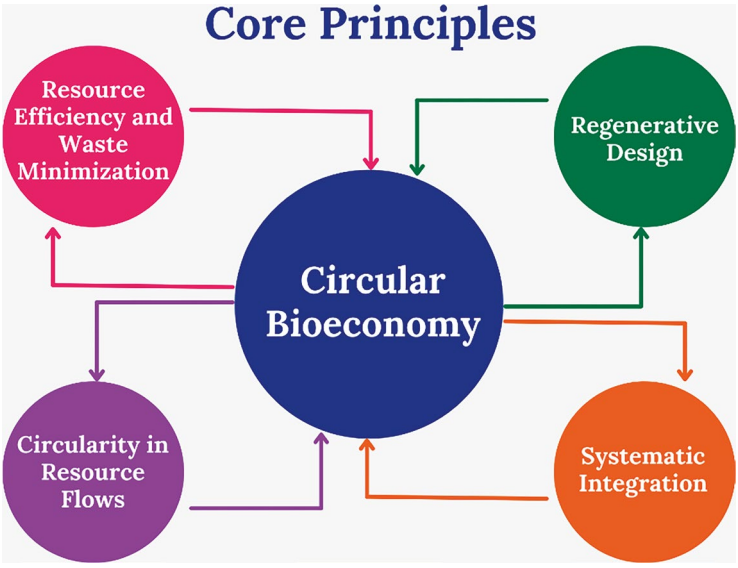

Fig. 9.2 Core principles of the circular bioeconomy

The third principle is resource efficiency and waste minimization. This principle emphasizes the optimal use of resources by reducing material loss through strategies like cascading, recycling, and reuse. The focus is on designing products and processes that minimize waste at every stage of the lifecycle, promoting the use of renewable inputs wherever possible and reducing dependency on finite resources (FNR, 2023; SEI, 2022).

Finally, systemic integration underscores the need for an interdisciplinary approach that combines insights from biology, engineering, and economics to optimize resource use and stimulate an extensive transition toward a CB. Successful CB initiatives often involve collaborations across sectors, for example, linking agricultural production with waste management systems to create bioenergy or integrating bio-based industries with carbon markets to improve economic feasibility. This interconnectedness ensures that bioeconomy solutions are economically viable, environmentally sustainable, and socially inclusive (UNECE/FAO, 2023; SEI, 2022).

In summary, the CB embodies a multidisciplinary effort, drawing insights from biology, engineering, and economics to optimize resource utilization. This interdisciplinary approach is essential for maximizing the value derived from bio-based resources and achieving environmental sustainability, economic resilience, and enhanced social welfare. Hence, CB positions itself among the critical models to address the complex challenges of climate change and resource scarcity.

9.3 Opportunities and Limitations of CB

The transition to a CB will reshape industries, foster innovation, and contribute to climate action. This transition offers several opportunities, such as the expansion of bio-based markets, job creation, and contributions to sustainability goals. However, this transition also faces significant limitations. To name a few, these are high initial costs of investment, uncertainties in policy commitments, and competition for land and resources. This section explores these opportunities and challenges in detail.

9.3.1 Opportunities for CB

Expansion of Bio-Based Markets

As industries transition from fossil fuels to more sustainable alternatives, a variety of bio-based products, including bioplastics, biofuels, bio-based chemicals, and biomaterials, are gaining popularity. The transition to bio-based products presents a significant growth opportunity for CB. The global bioeconomy is projected to be worth $7.7 trillion by 2030 (FAO, 2022), driven by climate and environmental targets, initiatives to reduce waste, and the transition away from fossil fuels.

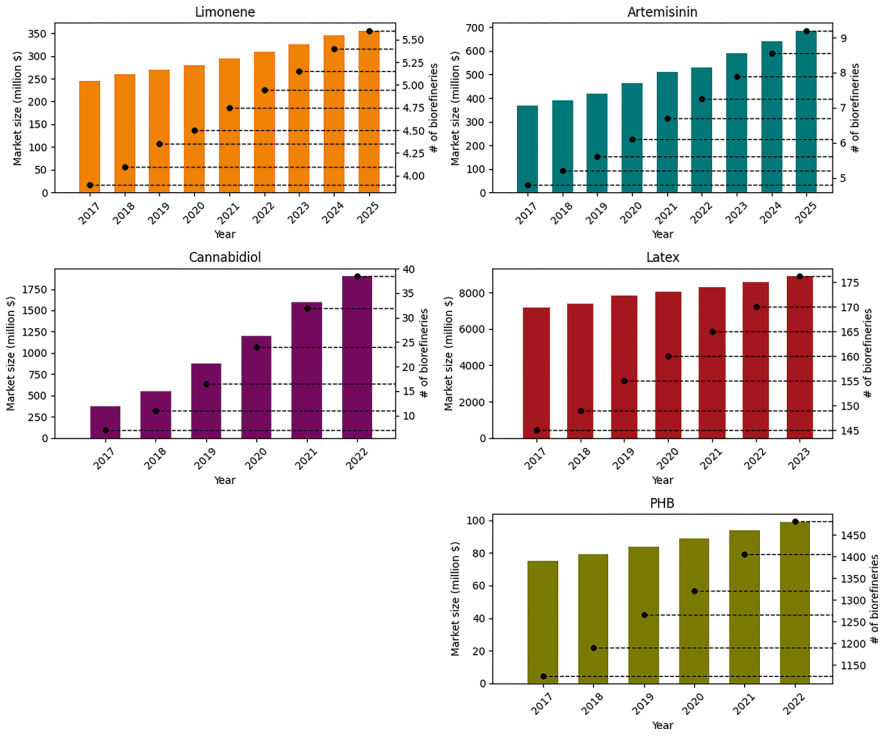

Fig. 9.3 Projected global market size for each bioproduct and the number of biorefineries needed to meet total global demand at the target minimum selling price of $2.50/ga (adapted from Yang et al., 2020)

To illustrate this growth potential, consider the projected market sizes for various bioproducts and the infrastructure required to meet this demand. Figure 9.3 shows the global market size projections for several bioproducts, including limonene, artemisinin, cannabidiol, latex, and polyhydroxybutyrate (PHB), and the number of biorefineries needed to satisfy these markets.[1]

These projections highlight the diverse scales of bio-based product markets: i) Small-volume, high-value markets (e.g., pharmaceuticals like artemisinin) and ii) Larger-volume markets (e.g., latex and PHB). Small-volume, high-value markets require only a few biorefineries to meet demand, as a single facility can easily produce enough to satisfy the market. Yet larger-volume markets need a far greater number of biorefineries due to higher demand and lower per-unit value.

[1] Notice that some projections end earlier than 2024. While these projections offer valuable insight into the potential of bio-based markets, the figures should be interpreted with caution, as some are based on older data and all are subject to change with new technological, economic, or policy developments. This underscores the importance of regularly updating projections to reflect current realities, especially in rapidly evolving fields like the bioeconomy.

The figure illustrates a potential challenge for bio-based markets: the mismatch in scale between production capacity and market size for certain high-value products, which could lead to market saturation and lower prices. Consequently, diversification across various bioproducts and processes within biorefineries may be essential to optimize output and avoid flooding the market with a sole product. Consequently, strategic planning and innovation in expanding bio-based markets to meet both economic and environmental objectives is quite critical.

Several international financial institutions, such as the European Investment Bank and the World Bank, are supporting the transition to more bio-based circular economy by providing funding for renewable energy and bioeconomy projects. In Europe, the European Bioeconomy Fund and InnovFin offer targeted financial support, encouraging investments in innovative bio-based technologies and processes. By channeling resources into the development of bio-based sectors, these institutions play a critical role in accelerating the shift to more bio-based solutions and spurring the development of new business models that integrate circular and bio-based principles.

These innovative business models not only improve industry sustainability but also create new economic opportunities. CB offers pathways for entrepreneurs, small businesses, and large corporations to build circular and bio-based economies. Economic incentives such as cost savings from resource efficiency, waste-to-value market processes, and favorable government policies (e.g., carbon pricing and renewable energy subsidies) play a key role in driving the adoption of these models. These incentives are explored further in Sect. 9.4.

Innovation, Business Models, and Employment

The CB fosters technological innovation and unlocks new business opportunities across various sectors, contributing to economic development and creating job opportunities (see Fig. 9.4). The bioenergy sector alone employed 3.58 million

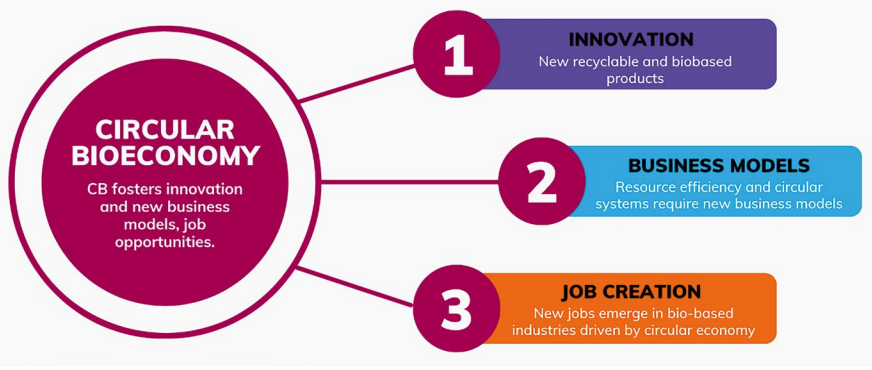

Fig. 9.4 Circular bioeconomy and its impact on innovation, business models, and employment

people globally in 2020, with continued growth projected as more regions adopt bio-based solutions (World Economic Forum, 2023). According to PricewaterhouseCoopers (PwC) India, as of August 2022, bioenergy projects in India supported approximately 0.43 million direct jobs and 0.66 million indirect jobs based on the country's total installed bioenergy capacity (PwC India, 2023). Notably, bioenergy projects generate at least twice as many direct jobs as solar and wind projects. This higher employment rate stems from the unique characteristics of bioenergy, which often require more extensive manual handling of biomass, ongoing maintenance, and processing activities than other renewable sources. Particularly, bioenergy projects create 12 to 18 white-collar jobs per MW, whereas wind projects generate only 7 to 8 jobs per MW and solar projects even fewer, with 5 to 10 jobs per MW (PwC India, 2023). Thus, the bioenergy sector offers valuable employment opportunities, especially in rural and economically underserved regions.

Bioenergy projects not only generate significant employment but also contribute to broader economic growth. By providing sustained job opportunities for both skilled and unskilled workers, bioenergy projects help increase disposable income and market spending. This increased spending drives higher private consumption, which, in turn, augments the country's Gross Domestic Product (GDP).

Moreover, evidence from organizations such as the OECD and FAO highlights the role of biorefineries and precision farming in boosting regional economies, increasing productivity, and creating new value chains. For instance, biorefineries are transforming how agricultural residues, forestry by-products, and other forms of biomass are converted into high-value products such as biofuels, biochemicals, and bioplastics. These innovations support local economies and stimulate investment in rural areas, helping to reduce dependency on imported goods (OECD/FAO, 2023). Additionally, precision farming and circular agriculture optimize resource use and minimize waste (FAO, 2022), leading to cost savings, higher productivity, and enhanced competitiveness in the agricultural sector. Together, these improvements can reinforce feedstock supplies for biorefineries and contribute to sustainable economic growth.

Bio-based materials and bioenergy are also transforming value chains by creating both centralized and decentralized production models. These models not only reduce environmental footprints but also offer new opportunities for entrepreneurship, particularly in local and rural contexts. Decentralized production enables communities to generate their own bio-based products and energy which contributes to economic resilience and self-sufficiency. For example, localized bioenergy cooperatives, where communities collaborate to produce renewable energy from agricultural or forestry residues, create jobs and reduce reliance on external energy sources, fostering local economic development (World Economic Forum, 2023).

One of the most transformative aspects of the CB lies in the emergence of new business models designed around circular principles, which address environmental challenges and enhance economic resilience. Circular business models extend the lifecycle of products, repurpose waste streams as new inputs, and optimize resource

efficiency. For instance, companies like LanzaTech are leading the way in carbon capture and utilization (CCU) technologies, converting industrial emissions into valuable biofuels, chemicals, and other materials (LanzaTech, 2022; ArcelorMittal, 2023). By turning what were once waste into marketable resources, these companies not only reduce carbon emissions but also generate entirely new markets, illustrating the economic and innovative potential of the CB.

Another emerging model is the circular bio-based value chain, which transforms agricultural residues, food waste, and forestry by-products into bio-based products, bioenergy, and biochemicals. Firms like Circular Systems are pioneering closed-loop systems that reduce waste, support sustainable production, and create new revenue streams. Such innovations offer opportunities for small businesses, entrepreneurs, and large corporations alike, generating jobs across various sectors (FAO, 2022).

Collaborative business models are also gaining basis in the CB space. These involve many stakeholders across sectors such as agriculture, energy, and manufacturing, who work together to optimize resource use and share the added value. Bioenergy cooperatives, for instance, represent a powerful example of community-driven circular models. Local communities pool resources to produce renewable energy, generating local jobs and fostering resilience. By diversifying income streams and strengthening local supply chains, these cooperatives help communities better withstand market fluctuations and environmental disruptions, ensuring greater resilience. Such collaborations highlight how CB fosters not only environmental sustainability but also economic and social stability.

Overall, these innovative business models not only improve industry sustainability but also create new economic opportunities. CB offers pathways for entrepreneurs, small businesses, and large corporations to build circular bioeconomies. Economic incentives such as cost savings from resource efficiency, waste-to-value market processes, and favorable government policies (e.g., carbon pricing and renewable energy subsidies) play a key role in driving the adoption of these models. These incentives are explored further in the section on economic viability.

The socio-economic benefits of CB are also evident. By creating jobs, supporting resilient supply chains, and fostering localized production, the CB enhances economic stability. Moreover, it aligns with the Sustainable Development Goals (SDGs) by addressing resource constraints and promoting social equity. CB helps build a more robust and inclusive economy by providing employment opportunities across different social groups and regions, especially in under-represented or economically challenged regions.

Contribution to Climate Targets and Resource Efficiency

Bio-based industries help decarbonize production systems by shifting away from fossil fuels. Thus, CB plays a critical role in reducing greenhouse gas (GHG) emissions (FAO, 2022). Bio-based industries also promote resource efficiency by minimizing waste and optimizing the use of renewable resources throughout their

lifecycles (World Economic Forum, 2023). Therefore, CB plays a critical role in mitigating climate change by promoting bio-based alternatives (e.g., biofuels and biochemicals) that can reduce reliance on non-renewable sources and GHGs, thus aligning with global climate goals, such as the Paris Agreement (Achillas & Bochtis, 2020).

To support the transition to bio-based alternatives, policy mechanisms such as carbon pricing and emissions trading schemes play a crucial role. These instruments help to internalize the environmental costs of greenhouse gas emissions and create market incentives for cleaner, bio-based solutions. Figure 9.5 illustrates the global adoption of carbon pricing mechanisms and emissions trading systems, both of which are critical tools for achieving climate targets. Figure 9.6 provides a more granular view, detailing the implementation of these mechanisms at subnational levels in the European Union (EU), China, and Canada. As stated in World Bank (2024, p. 21), instruments "under development" are where a government is actively working toward the implementation of a carbon pricing instrument, formally confirmed by official government sources. If a government has announced its intention to work toward the implementation of a carbon pricing instrument, confirmed by official government sources, the instrument is "under consideration." For those countries that have both existing (implemented) carbon pricing instruments and others that are still either "under development" or "under consideration," the map reflects the status of the former.

The CB also enhances resource efficiency by encouraging circular practices, where biological materials are reused and recycled, reducing waste generation. The resources are kept in productive use for as long as possible, minimizing the need for new raw inputs. Particularly, circular systems, such as closed-loop production, ensure that by-products and waste streams are continuously fed back into the production cycle, improving material efficiency and reducing environmental impacts.

Consequently, by reducing resource use, enhancing resource efficiency, and lowering GHGs, the CB is a strong step toward contributing to climate action and sustainability targets. This highlights the CB's potential to deliver both on the environmental and economic promises of the twenty-first century by transforming industries while maintaining alignment with international climate agreements.

Access to Financial Support and Incentives

Due to the rising concerns over climate change, environmental pollution, and their impacts on public health, governments and organizations worldwide are offering an increasing collection of financial instruments such as grants, tax incentives, and targeted low-interest loans. This shift is essential not only for addressing the environmental and economic costs of pollution and resource depletion but also for driving the green transition and supporting sustainable economic growth. Additionally, this shift and tools provide financial ease for costly bio-based initiatives, making them economically more viable.

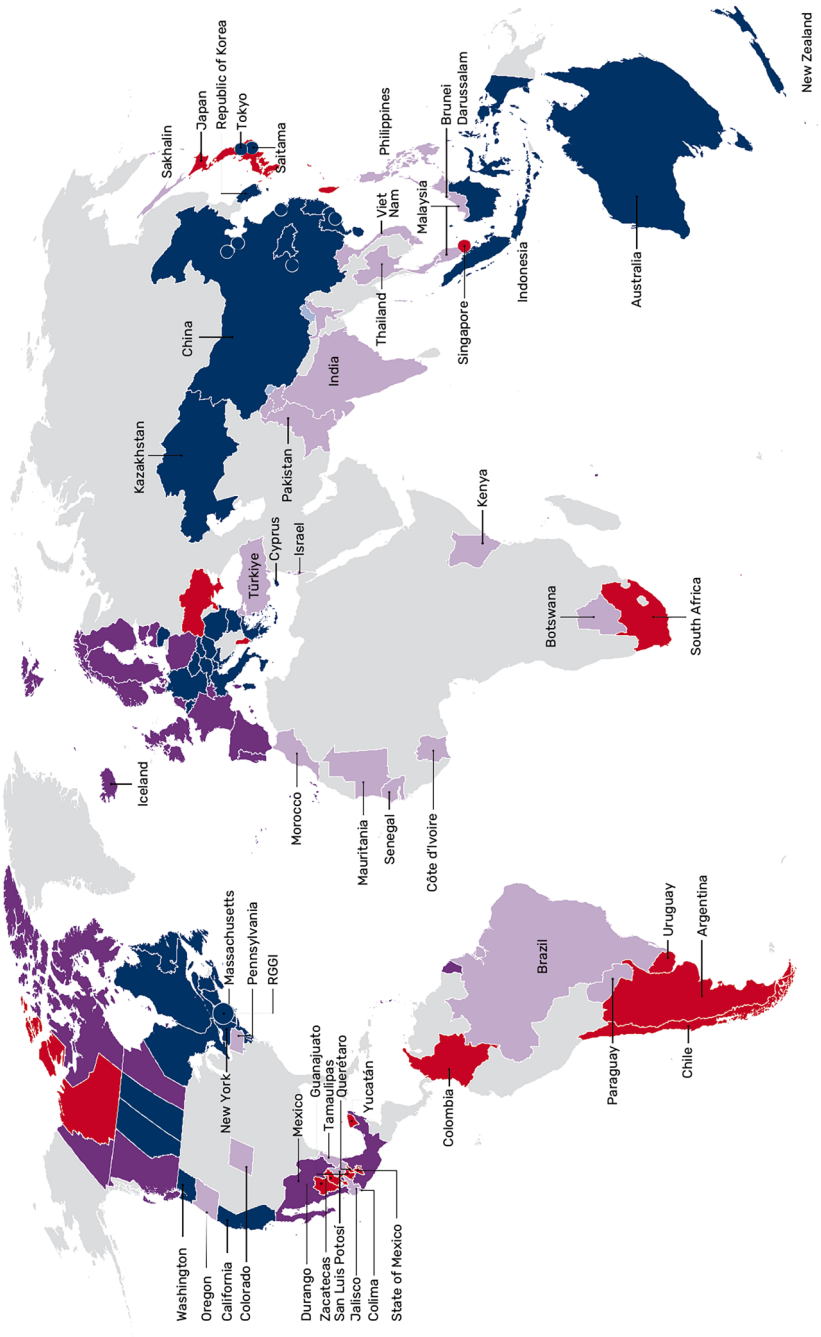

Fig. 9.5 Global adoption of carbon pricing and emissions trading systems (adapted from World Bank, 2024, Fig. 9.4)

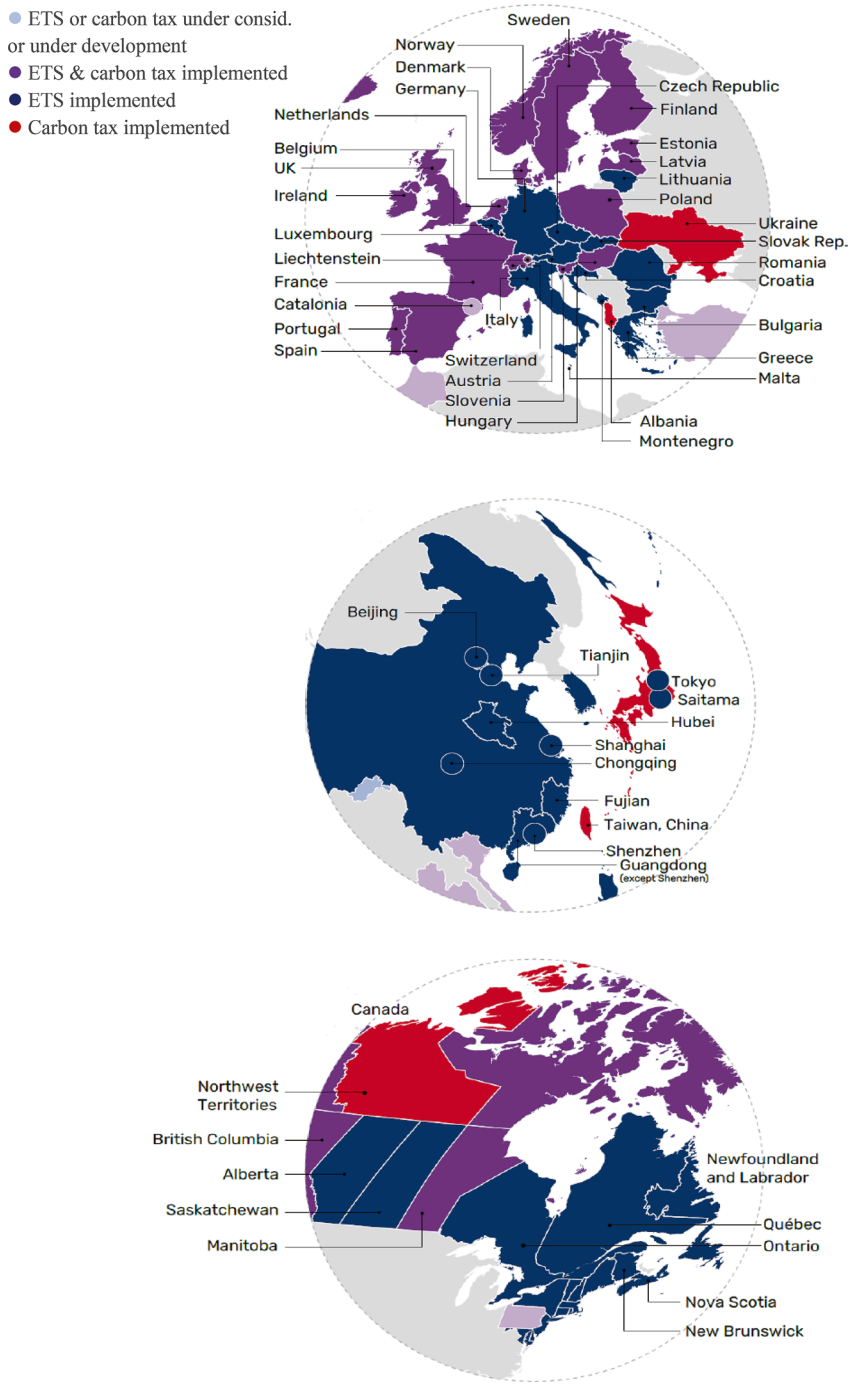

Fig. 9.6 Mechanisms at the subnational level in the EU, China, and Canada (adapted from World Bank, 2024, Fig. 9.4)

Programs such as the European Bioeconomy Fund and the LIFE Programme demonstrate the positive impact of financial instruments on the CB by reducing investment risks through grants and subsidies, thereby driving private sector interest in sustainable and regenerative projects. Through such initiatives and the financial tools mentioned above, policymakers and industry leaders can move beyond conventional sustainability practices and foster systems where resources are continuously cycled back into productive use, thereby improving the endurance and sustainability of the bioeconomy.

9.3.2 Limitations and Challenges of the CB

High Initial Capital Costs

As discussed in Sect. 9.3.1 (Access to Financial Support and Incentives), bio-based initiatives are highly capital-intensive, requiring substantial upfront investment in infrastructure such as advanced recycling facilities and biorefineries. These projects face long payback periods and significant technological uncertainties, which can deter private investors, especially in sectors lacking stable policy frameworks (Skondras et al., 2024). In markets where environmental externalities, like pollution, remain unpriced, the failure to account for these costs results in a competitive disadvantage for bio-based initiatives, as more polluting practices retain their cost advantage. Furthermore, without targeted subsidies or financial incentives, innovators in bio-based technologies face disincentives to push the frontiers of innovation, knowing that their costly advances may be readily adopted by others without bearing equivalent development costs.

These barriers underscore the critical need for robust policy frameworks, which could include pricing mechanisms for environmental externalities, dedicated subsidies, and intellectual property protections to support long-term viability and innovation. Additionally, public–private partnerships and risk-sharing arrangements are essential to balance the high initial risks of bio-based projects and to establish a basis for sustainable growth. Through such measures, governments can help shift the market toward cleaner practices, thereby reducing reliance on conventional, polluting technologies while promoting innovation in the bioeconomy.

Policy and Regulatory Inconsistencies

For the CB to reach a certain level of share in the economy, it requires a stable and supportive policy environment. Policies that guide investments, set environmental standards, and incentivize sustainable practices are vital in helping bio-based industries take root and grow sustainably. However, inconsistent or conflicting policies and regulations, whether across or within countries, can pose significant barriers to CB initiatives. These inconsistencies introduce uncertainties that are discouraging investments and prevent faster adoption of bio-based practices.

Conflicting policies or unpredictable regulatory shifts made by the central authority, such as sudden and unpredictable changes to biofuel standards, unforeseen changes in carbon pricing mechanisms, or inconsistent modifications to subsidies and incentives for green projects create a volatile environment for businesses operating within a country. Bio-based industries, which often require significant upfront investments and have long payback periods, are particularly vulnerable to these types of uncertainties.[2]

Specifically, when companies invest heavily in bio-based technologies under a favorable set of policies, only to face abrupt regulatory shifts that reduce the viability of their operations, they risk substantial financial losses. This risk deters companies from committing resources to bio-based projects and this situation worsens when national policies appear erratic or lack a clear, long-term trajectory (Helm et al., 2003). As is well documented, Investors prefer stable, predictable environments in which they can reliably project their returns (Dixit & Pindyck, 1994). Consequently, when policies are inconsistent or subject to frequent change, investors may opt to delay, reduce, or even withdraw their investments, redirecting capital to more predictable environments.

To avoid such outcomes, establishing a stable and predictable policy framework in countries would foster market environments where companies and investors would feel confident about committing to long-term bio-based projects. With clear, harmonized, and stable regulations, countries can attract greater investment into the bioeconomy, thereby facilitating the shift away from conventional and polluting industries and promoting sustainable development (OECD, 2019, European Commission, 2020; Helm et al., 2003).

Technological and Market Gaps

Although bio-based technologies hold significant potential to reduce our reliance on fossil fuels and reduce environmental harm, many remain in their nascent stages and face significant challenges, such as high costs and energy demand. For example, bioprocesses such as advanced fermentation require substantial energy inputs, which can offset their environmental benefits if not carefully managed (FAO, 2022). If we are to achieve truly sustainable solutions, we must ensure that these inputs do not undermine the intended environmental benefits.

Addressing these challenges demands ongoing innovation at multiple levels. Yet, the need for innovation extends beyond just technological improvements. It encompasses an economic dimension that is equally crucial. Investing in research and development is a necessary step, but, as discussed above, we also need comprehensive and innovative policy frameworks, new business models, and sustainable

[2] Dixit and Pindyck (1994, pp. 225–230) highlight that regulatory uncertainty can deter investment in capital-intensive industries, where firms rely on policy stability to secure returns over the long term.

economic strategies that can help mitigate the financial risks associated with bio-based projects.

The economics of scale is another factor worth mentioning. While these technologies are currently costly and inefficient, increasing production volume can bring down costs and improve efficiencies, provided that the initial hurdles can be overcome. As more bio-based technologies enter mainstream production, the potential for learning-by-doing can help reduce costs. However, this too is influenced by the policy environment. Early-stage subsidies or tax credits for bio-based products could accelerate the scaling process, allowing these technologies to become competitive faster. Ultimately, the transition from niche to mainstream requires coordinated efforts from governments, investors, and innovators to make these technologies economically viable.

Food Security and Competition for Land

The increasing demand for land to produce bioenergy crops or raw materials for bioplastics can create significant tensions between biomass and food production. This issue not only raises food security concerns but also puts additional pressure on ecosystems, as the conversion of natural or agricultural lands to bio-based production can lead to biodiversity loss and degradation of vital habitats. When food and biomass production compete for the same limited resources, the resulting pressure on food supply can drive up food prices, disproportionately affecting lower-income communities in vulnerable regions (World Economic Forum, 2023).

Prioritizing non-food biomass sources, such as algae, crop residues, and other agricultural by-products, is a promising approach to mitigate these risks. Research indicates that algae, for example, can be cultivated on non-arable land, often with minimal freshwater requirements, thereby reducing competition for food crops. Agricultural residues, too, offer a viable alternative, as they can be used without displacing food production or adding new pressures on arable land (FAO, 2022).

Again, policymakers can play a pivotal role here. By establishing incentives or standards that prioritize non-food biomass sources, they can guide industry players toward more sustainable production choices. Moreover, frameworks that emphasize land-use efficiency, including the restoration of degraded lands for biomass cultivation, can help alleviate some of these tensions. Collaboration across sectors such as agriculture, bioenergy, and environmental protection will also be critical to develop solutions that support both food security and sustainable growth of bio-based industries.

Before moving to the next section on economic evaluation, it is crucial to acknowledge that the shift toward a fully circular bioeconomy is a dynamic and iterative process. As technology advances and new insights emerge, economic structures, policies, and regulations must adapt accordingly to ensure that circular resource flows and regenerative systems remain both feasible and effective over time (Zilberman et al., 2018; Wesseler & von Braun, 2017).

9.4 Economic Viability in the Circular Bioeconomy: Limitations of Traditional Metrics

Economic evaluation plays a pivotal role in determining the viability of bio-based projects. However, traditional metrics like Net Present Value (NPV), Internal Rate of Return (IRR), and simple payback periods often fall short in capturing the full range of benefits and challenges associated with CB investments. These conventional tools were designed for linear economic models, where costs and benefits follow straightforward paths. In contrast, bio-based systems operate within complex, dynamic, and circular frameworks that demand a different approach to economic analysis.

To start with, bio-based systems are characterized by cascading resource flows where by-products serve as valuable inputs for secondary processes. Furthermore, government policies such as carbon pricing, renewable energy incentives, and tax exemptions play a crucial role in shaping the financial viability of new technologies, including bio-based systems. While high initial investment costs are common to all emerging technologies, bio-based projects face additional complexities due to their integration into multiple sectors, such as agriculture, energy, and waste management, each governed by distinct regulatory frameworks.

Bio-based systems also rely heavily on externalities being priced correctly (e.g., carbon emissions or biodiversity impacts). Inconsistent or poorly coordinated policies across sectors can disproportionately impact the profitability of bio-based initiatives, making their evaluation particularly challenging. For instance, a bioenergy project might benefit from renewable energy subsidies but face land-use restrictions that increase feedstock costs, creating conflicting incentives that traditional metrics often fail to capture.

To accurately assess the economic viability of CB projects, economic metrics must be adapted to reflect their unique characteristics and value propositions. Developing tailored metrics that explicitly incorporate these additional revenue streams is essential for providing a more accurate financial assessment. Moreover, given the dynamic policy environment in which CB projects operate, scenario-based analyses can be instrumental in evaluating the potential impact of changing policies. Therefore, complementing scenario-based analyses with stochastic models, particularly those associated with regulatory and market fluctuations, will allow for a more robust consideration of uncertainties.

Expanding traditional economic metrics to include monetized values of avoided emissions, public health improvements, and biodiversity gains represents another critical step forward. However, achieving this comprehensively is a challenging task, as many of these benefits are difficult to quantify and monetize accurately. While such integration may never fully capture the broader societal impacts, even partial inclusion can significantly enhance the quality of economic evaluations.

In addition, extending the evaluation period to account for the long-term benefits of bio-based projects is very crucial. Here, the choice of discount rate becomes a pivotal factor, as the discount rate determines how future environmental and social

benefits are valued relative to present-day outcomes. Selecting an appropriate rate is not only a technical decision but also an ethical one, as it would reflect societal priorities regarding intergenerational equity and sustainability.

9.4.1 Competitiveness of Bio-Based Products: The Role of Levelized Cost

Evaluating the competitiveness of bio-based production requires economic metrics that i) reflect their unique production characteristics and ii) provide a basis for comparison with alternative technologies.

A commonly used approach is to calculate an indicator of the total cost of production over the lifetime of the project. In this context, the Levelized Cost of Production (LCOP) emerges as a critical metric. It measures the per-unit cost of producing a specific product (e.g., per ton, per liter, or per megajoule) over the financial lifetime of the project. It is calculated as the present value of all costs, such as capital expenditures (CAPEX), operating expenses (OPEX), and feedstock costs, spread over the lifetime output, $\sum_{t=1}^{T} Q_t$, of the facility. The present value calculations are based on the Weighted Average Cost of Capital (WACC), which reflects the project's discount rate.

LCOP ensures comparability across different technologies by expressing costs in standardized, per-unit terms. It is calculated as follows:

$$\mathrm{LCOP_t} = \frac{\sum_{t=1}^{T} \frac{\left(\mathrm{CAPEX}_t\right) + \left(\mathrm{OPEX}_t\right)}{\left(1+\mathrm{WACC}\right)^t}}{\sum_{t=1}^{T} \frac{Q_t}{\left(1+\mathrm{WACC}\right)^t}}$$

Here, the subscript t denotes the period when the costs accrue or production takes place.

Yet, to guide investment decisions accurately, LCOP must be adapted to account for the specificities of the bio-based systems.

9.4.2 LCOP for Bio-Based Products

Because of the peculiarities of CB, the LCOP needs to be tailored to reflect the distinct features of bio-based products. Key considerations include the cascading resource flows, feedstock prices, and environmental benefits, not to mention the policy tools and regulations concerning bio-based production.

First, bio-based systems generate multiple co-products at various stages. These cascading flows offset production costs and enhance resource efficiency by reusing materials across multiple applications. Consequently, these additional revenue streams improve project viability and require explicit inclusion in LCOP calculations to avoid underestimating the economic potential of the bio-based projects. As we will discuss later, in a biojet fuel production facility, biochar and electricity sales can significantly lower the LCOP by providing stable revenue streams.

Furthermore, bio-based projects face variability in feedstock prices due to seasonality, transportation logistics, and market dynamics. Sensitivity analyses that model feedstock price fluctuations are critical for producing realistic LCOP estimates. In CB systems, however, reliance on locally sourced feedstocks or closed-loop supply chains can partially mitigate price variability while supporting regional economies.

In addition, bio-based projects often reduce GHG emissions and generate carbon credits. Unlike other clean technologies, cascading resource flows in bio-based systems amplify these environmental benefits by enabling multiple cycles of resource utilization, reducing overall emissions and resource extraction. Including these benefits, whether through carbon revenue streams or avoided emission costs, ensures the LCOP reflects the broader societal value of bio-based products.

Therefore, to understand whether bio-based products are competitive, it is vital to ensure that co-products and externalities are adequately accounted for in the LCOP computations. For instance, without incorporating co-product revenues, the levelized cost of energy (LCOE) for bioenergy systems may appear higher than the LCOE for conventional energy, potentially deterring investments despite the benefits of bio-based solutions. Yet, quantifying externalities can be a daunting task. In addition, changing regulations and regulatory costs along with the evolving nature of bioeconomy shaped by global trends, such as digitization, (de-)globalization, urbanization, science, and changing preferences further complicate the measurement of economic performance (Wesseler & von Braun, 2017). Accurately reflecting these concerns in LCOP analyses is crucial for revealing the true economic and societal value of bio-based systems.

In the following section, we present a case study on advanced biojet fuel production. The study demonstrates how LCOP can be adjusted to account for co-products, offering a concrete illustration of improving LCOP analyses for bio-based systems. Note that while the case study highlights practical steps for integrating co-products into a LCOP computation, it does not propose an integrated measure that accounts for the additional complexities and externalities discussed above.

9.4.3 Case Study: Advanced Biojet Fuel Production

Advanced biojet fuels offer a sustainable alternative to conventional jet fuels, presenting significant environmental and economic benefits. These fuels are derived from renewable resources such as agricultural residues and represent a critical strategy for reducing GHG emissions in the aviation sector. Two primary production

pathways stand out as promising options for achieving decarbonization (Van Dyk & Saddler, 2024; U.S. Department of Energy, 2024). The first is the Alcohol-to-Jet (AtJ) pathway, which converts intermediates like ethanol and butanol into sustainable aviation fuels, reducing reliance on fossil-based feedstocks (U.S. Department of Energy et al., 2024 and van Dyk & Deshpande, 2025). The second is Fischer–Tropsch (FT) synthesis, which transforms syngas derived from biomass into long-chain hydrocarbons, providing a flexible and scalable approach to producing biojet fuel (Doliente et al., 2020). While the AtJ pathway contributes to sustainability goals, it has rather limited potential in advancing the principles of the CB compared to the FT pathway (Van Dyk & Saddler, 2021, pp. 46, 76–77). Thus, in the following, we will focus our discussion on the FT pathway and its broader implications.

The FT pathway generates a diverse portfolio of co-products that play an essential role in enhancing the economic feasibility of biojet fuel production. One notable co-product is solid residues, such as biochar, which can improve soil fertility, sequester carbon, and even serve as an energy source when combusted, thereby reducing operational costs (Woolf et al., 2010). Additionally, the FT process produces excess heat and electricity, which can be utilized internally to lower energy expenses or sold to external markets, creating additional revenue streams, especially in regions with supportive renewable energy policies.

Another critical aspect of the FT process is the production of chemical by-products, including methane, ethane, and propane. These compounds can serve as internal fuel sources to improve operational efficiency or be sold externally as liquefied petroleum gas (LPG), providing yet another avenue for revenue generation (Van de Loosdrecht et al., 2013).

Together, these co-products enhance the economic sustainability of the FT pathway. While challenges such as high capital costs and feedstock logistics remain, the FT process exemplifies how advanced technologies can align environmental objectives with economic incentives.

To quantitatively assess the economic viability of the FT process, we modify the LCOP we introduced earlier and define it as the levelized cost of fuel (LCOF). Unlike before, the total periodic costs now include feedstock costs and are now offset by revenues from co-products over the project lifetime. Accordingly, the LCOF can be expressed as follows:

$$\mathrm{LCOF}_t = \frac{\sum_{t=1}^{T}\left[\frac{\left(\mathrm{CAPEX}_t\right)+\left(\mathrm{OPEX}_t\right)+\left(\text{Feedstock Costs}_t\right)-\sum_{j=1}^{n}R_{j,t}}{\left(1+\mathrm{WACC}\right)^t}\right]}{\sum_{t=1}^{T}\frac{Q_t}{\left(1+\mathrm{WACC}\right)^t}}$$

where *F* in LCOF stands for fuel.

In the context of the FT synthesis, feedstock costs encompass the expenses incurred in sourcing, transporting, and preparing the biomass required for the process. Unlike fossil-based feedstocks, biomass such as agricultural residues, forestry by-products, or dedicated energy crops demand additional preparation steps to

optimize its conversion into syngas. These steps often include drying, size reduction, and sometimes even pre-treatment to ensure efficient gasification. The feedstock costs for FT systems can exhibit variability depending on the logistics, seasonal availability, and market competition for biomass resources.

Moreover, considering our discussions above, the FT pathway generates valuable co-products, which can significantly enhance its economic viability. Revenues from these co-products (e.g., biochar, methane, ethane, and excess heat and electricity), represented by the sum of R_j for $j = 1, 2, \ldots, n$ are critical in offsetting the production costs of the primary biofuel.

While the FT pathway's co-products significantly strengthen economic feasibility, accurately accounting for these benefits in practice remains challenging. Assessing the true competitiveness of bio-based systems requires robust methods that can capture externalities, regulatory dynamics, and the evolving nature of the bioeconomy (Wesseler & von Braun, 2017).

9.4.4 Adding Financial Instruments

Policy tools and financial instruments play a critical role in shaping the LCOP for bio-based systems. Direct monetary incentives, such as grants from programs like the LIFE Programme, can offset CAPEX, significantly lowering the upfront costs of constructing bio-based infrastructure. Accelerated depreciation schemes further hasten the capital cost recovery, improving cash flows and reducing financial risks for investors. On the other hand, tax incentives, including credits or exemptions for bio-based materials, enhance the profitability of bio-based projects by lowering the effective tax burden, making bio-based systems more competitive with fossil-based alternatives.

Soft loans and equity financing mechanisms also contribute to the feasibility of bio-based projects. For example, the European Circular Bioeconomy Fund (ECBF) supports high-potential and high-risk bio-based ventures by providing low-interest loans or equity investments, which are particularly valuable during late-stage project development. These financial instruments not only reduce the WACC, which, as we know, is a very critical component in LCOP computations, but also improve investor confidence in bio-based projects.

Moreover, environmental regulations and incentive programs have direct implications for LCOP as they can create new revenue streams for bio-based production. For instance, carbon credits generated from GHG emissions can be monetized and effectively lower the per-unit cost of fuel production. Waste reduction policies and recycling initiatives promote the cascading use of resources, thereby reducing the OPEX and improving production efficiency. Quantifiable environmental benefits, such as avoided carbon taxes or waste management savings, can also be integrated into LCOF calculations, ensuring a more accurate representation of the true financial and environmental value of bio-based products.

Incorporating these financial and policy tools into the LCOF framework demonstrates how well-designed economic and regulatory mechanisms can align environmental objectives with economic feasibility. By integrating such instruments, the LCOF metric not only quantifies the competitiveness of bio-based systems but also highlights their potential to serve as a basis for CB.

Related financial and policy tools can be incorporated to the LCOF to yield

$$\mathrm{LCOF}_t = \frac{\sum_{t=1}^{T}\left[\frac{\left(\mathrm{CAPEX}_t\right)+\left(\mathrm{OPEX}_t\right)+\left(\text{Feedstock Costs}_t\right)-\sum_{j=1}^{n}R_{j,t}-\sum_{k=1}^{m}P_{k,t}}{\left(1+\mathrm{WACC}\right)^t}\right]}{\sum_{t=1}^{T}\frac{Q_{i,t}}{\left(1+\mathrm{WACC}\right)^t}}$$

where $P_{k,t}$ for $k = 1, 2, \ldots, m$ represent the cost offsets achieved through effective policy instruments. To ensure an accurate and consistent representation, the policy-driven reductions in both CAPEX and OPEX are included through $\sum_{k=1}^{m} P_{k,t}$.

9.4.5 A Critical Component in Economic Viability: WACC

WACC is a cornerstone metric in evaluating the financial viability of projects, particularly for low-carbon technologies for which investment decisions are highly sensitive to capital costs. Serving as the discount rate in net present value (NPV) computations, WACC influences project evaluation, investment decisions, and the determination of minimum acceptable returns. Essentially, WACC reflects the cost of financing a project through both debt and equity, weighted according to their proportions in the capital structure.

Several factors critically shape the WACC for a project. First, the cost of debt and equity financing is directly tied to perceptions of risk. Projects perceived as higher risk face higher equity costs and borrowing rates, leading to a higher WACC. Second, the project's capital structure plays a pivotal role. Specifically, a higher proportion of low-interest debt generally reduces the WACC, improving project attractiveness. Finally, external conditions, such as market interest rates, inflation, and government policies like subsidies or tax credits, directly affect financing costs, further influencing WACC.

WACC's impact can vary significantly from one sector to the other. For instance, for fossil fuel technologies, fuel costs tend to be the dominant driver of investment decisions. Conversely, renewable energy technologies, such as concentrated solar power (CSP), wind onshore, and solar photovoltaic (PV) systems, are particularly sensitive to changes in WACC due to their high upfront capital requirements.

To illustrate this sensitivity, let us consider a simple example comparing a capital-intensive technology (e.g., solar PV) with a fuel-intensive one (e.g., combined-cycle power plant). Not all the figures used in this example are based on actual data but are broadly representative of real-life application conditions. While simplified, this example captures the key cost dynamics of capital-intensive renewable technologies versus fuel-intensive fossil fuel generation. For simplicity, we assume away any policy-driven reductions in the computations.

In our example, we assume a standardized plant size (100 MW) with annual operation hour. For solar PV, we use a higher CAPEX (e.g., $1100 per kW) and a lower OPEX (e.g., $5 per kW per year), along with a capacity factor of 23.3%.[3] For a combined-cycle power plant, CAPEX is lower (e.g., $900 per kW), but OPEX is significantly higher (e.g., $150 per kW per year) with a capacity factor of 58.8%. We assume that both facilities will have a lifetime of 25 years ($T = 25$). The capital recovery factor (CRF) is computed as

$$\mathrm{CRF} = \frac{\mathrm{WACC} \times \left(1+\mathrm{WACC}\right)^{T}}{\left(1+\mathrm{WACC}\right)^{T}-1}.$$

CRF is a financial ratio that converts a project's capital cost into equivalent annual costs over its lifetime. It takes into account the time value of money by incorporating the WACC and the project's lifetime, T. Essentially, the CRF provides a way to spread the capital cost over the years the project is expected to operate. This factor is then multiplied by the CAPEX to estimate the annual cost used in calculating the LCOE or, in our modified framework, the LCOF.

The LCOE is then computed to yield

$$\mathrm{LCOE}_{t} = \frac{\mathrm{CAPEX} \times \mathrm{CRF} + \mathrm{OPEX}}{Q}$$

where the annual energy output, Q, is determined by the plant capacity, capacity factor, and total hours in a year (8760 h/year). Note that we factored out the discounted sums in the denominator and numerator as we assume constant annual energy production and constant annual OPEX.

Figure 9.7 illustrates how different WACC rates can affect the LCOEs, and therefore, the competitiveness of the two energy generating technologies. Assuming that the WACC can take values from 0.02 to 0.12, we see that for WACC values below 5%, solar PV becomes competitive against the combined-cycle power plant. Yet, for WACC rates higher than 5%, we can observe that the LCOE for solar PV rises faster; hence, underscoring the WACC's critical role in determining the LCOE generation.

Sweerts et al. (2019) illustrate how changes in WACC can affect the competitiveness of six renewable and three fossil fuel technologies in several African countries.

[3] The capacity factors are obtained from Tables 6.07.A-B in EIA (2025).

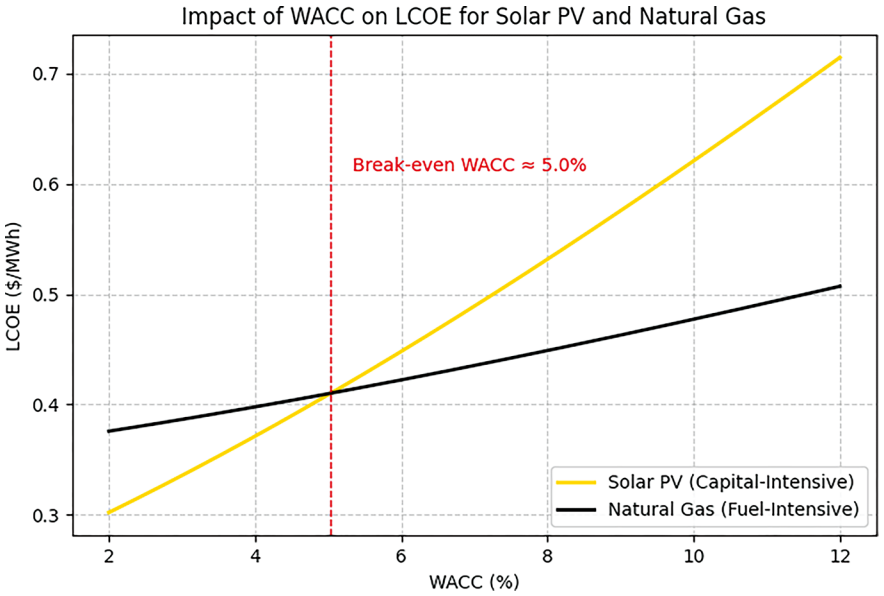

Fig. 9.7 Impact of WACC on LCOE

The authors break down total costs into debt, equity, OPEX (fuel and O&M), and capital depreciation. The results indicate that, while renewable technologies like wind and solar energy are competitive at low WACC values in comparison to natural gas- and diesel-based electricity generation, they become more expensive than even diesel generators at a high WACC value. Furthermore, onshore wind power becomes cost-competitive with natural gas at a WACC of 13%, whereas solar PV requires a WACC of 6%. CSP remains cheaper than diesel only when WACC is below 9%. In contrast, geothermal power proves relatively inexpensive, outperforming natural gas and diesel under all WACC scenarios. According to the authors' calculations, small hydropower reaches cost-competitiveness with coal and natural gas at WACC values of 2% and 21%, respectively. Moreover, large hydropower maintains cost-competitiveness with coal until the WACC reaches 22%. Additional analyses confirm that renewable energy technologies are most sensitive to changes in WACC, while fossil-based technologies are more sensitive to changes in fuel costs.

As another example to the importance of WACC for the unit cost of production, consider Fig. 9.8 which illustrates the average capacity factor (CF) of solar PV systems across European countries from 1979 to 2024. Darker shades represent higher capacity factors, indicating regions with higher solar radiation and therefore, more favorable solar energy conditions. All else equal, one would expect the areas with higher CFs to yield lower LCOE rates. However, with different financing conditions, here, differences in WACC rates, a completely different picture can emerge.

Accordingly, Bódis et al. (2019) investigate the LCOE for rooftop solar systems in the EU, focusing on the localized unit costs of electricity generation. The results

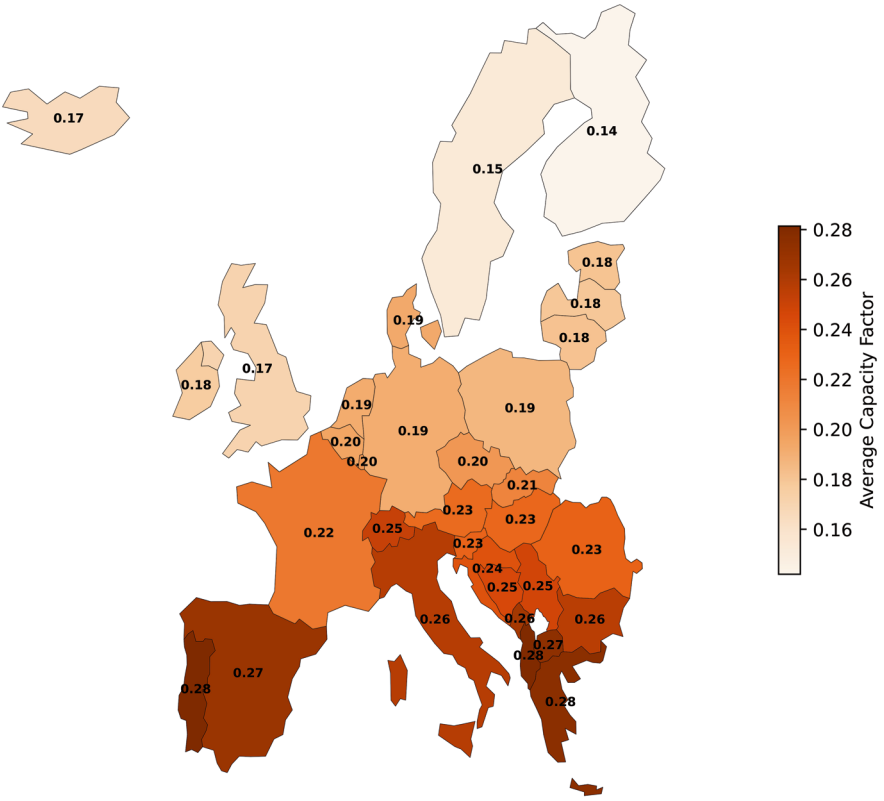

Fig. 9.8 Average Solar PV Capacity Factor (1979–2024). The capacity factor data is sourced from the Copernicus Climate Data Store (CDS) SIS Energy Derived Reanalysis dataset (https://cds.climate.copernicus.eu/datasets/sis-energy-derived-reanalysis?tab=download), while country boundaries are derived from the Natural Earth dataset with 1:50 million scale (https://www.naturalearthdata.com/).

revealed a wide range of LCOE values, from €0.06/kWh to €0.32/kWh (see Fig. 9.5 in Bódis et al., 2019). The primary driver of this variability was found to be differences in WACC, rather than being strictly tied to CF values. Interestingly, countries with high solar energy potential, such as Greece and Bulgaria, were found to have high capital costs and, consequently, higher LCOE values. Conversely, some EU countries with less favorable solar energy potential, such as Denmark and Belgium, exhibited lower LCOE values due to their lower capital costs. This counterintuitive finding underscores the critical role of financing conditions in shaping the cost-competitiveness of rooftop solar systems.

The sensitivity to financing conditions is not unique to renewable energy systems; it naturally extends to CB investments, where high capital costs increase the importance of WACC. Accordingly, reducing WACC can play a transformative role in improving the cost-competitiveness of bio-based systems, particularly those requiring significant upfront investments.

9.4.6 Reducing WACC

Since a country's WACC can significantly impact the cost of energy transition, the question of how to reduce it becomes a key issue. Potential solutions for lowering WACC include implementing policies and regulations to reduce country risk premiums, improving the investment climate, and diversifying the economy.

While sovereign Credit Default Swap (CDS) spreads and the WACC are not directly linked, they are indirectly connected through factors such as the cost of debt, market's perception of a country's economic and political risks, and currency exchange rate risks. An increase in a country's CDS spreads can influence the financing costs for companies operating within that country, thereby impacting their WACC. Company-specific credit risk premiums also play a role in this relationship, as these premiums reflect a firm's creditworthiness and are often influenced by similar factors that drive sovereign CDS spreads.

High CDS values signal heightened financing costs and indicate that borrowing needs may be met under more stringent conditions. This poses a challenge for securing the financial resources necessary for green transformation and economic growth, particularly in emerging economies. As discussed by PwC Australia (2018, pp. 2–3), sovereign risk factors reflected in CDS spreads are a crucial component in determining country risk premiums, which in turn feed into WACC calculations for businesses. Similarly, the Bank for International Settlements (2007, pp. 5) highlights how sovereign spreads encompass not only expected default risks but also the broader risk premium demanded by investors, linking them indirectly to corporate financing costs.

Figure 9.9 illustrates the extent to which the financial risk exposure of insurance companies (ICs) is influenced by the sovereign debt (e.g., government bonds or similar debt instruments issued by the country's government) they hold. Specifically, it shows that a 1% increase in the CDS spread of sovereign portfolio leads to a measurable rise in the risk premium of insurance companies, with the effect being more pronounced for those most exposed to sovereign portfolios. This finding highlights the interconnectedness of sovereign risk and institutional financial health. The figure also emphasizes dynamics during periods of heightened market stress, such as in March 2020, when sovereign CDS spreads surged globally amid the COVID-19 pandemic. This period saw amplified risk premia for the most exposed insurance companies, underscoring how systemic risks can propagate through the financial sector during crises (Hardy & Zhu, 2023).

This relationship is particularly relevant for understanding the WACC, as it demonstrates how sovereign risk indirectly affects the cost of debt for businesses operating within that country. The spillover from sovereign CDS spreads into the risk premia of financial institutions can translate into higher borrowing costs, which elevate the cost of debt, a critical component of WACC. Moreover, the increased cost of financing for insurance companies can cascade to the broader economy, influencing corporate financing conditions and investment decisions. This is particularly significant for businesses in countries with high sovereign risk, as elevated

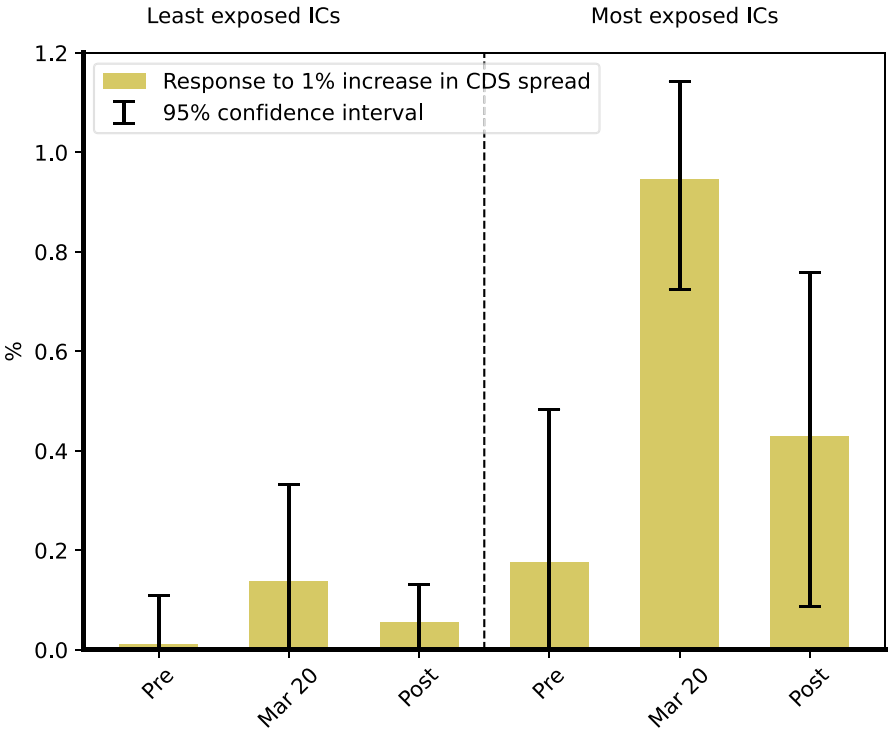

Fig. 9.9 ICs' risk premia (adapted from Hardy & Zhu, 2023)

WACC can dampen their ability to invest and grow, further perpetuating economic challenges. The figure thus underscores the systemic implications of sovereign risk for financial stability and corporate financing, particularly during periods of economic stress.

Reducing the country's risk premium requires enhancing institutional quality and ensuring economic stability. This can be achieved by controlling inflation and interest rates, increasing transparency in debt management and financial reporting, and maintaining fiscal discipline. Controlling inflation and interest rates can be accomplished through central bank monetary policies and government fiscal policies. In monetary policy, central banks aim to keep inflation at target levels by adjusting interest rates and regulating money supply, while fiscal policy involves governments using spending and taxation measures to stabilize the economy.

Efforts to improve the investment climate can involve enacting new regulatory reforms, prioritizing infrastructure investments, and providing legal guarantees for investors. These measures can build trust among domestic and international investors, thereby reducing capital costs.

Additionally, diversifying the economy helps mitigate risks associated with excessive reliance on specific sectors. For instance, in the energy sector, investing in renewable energy sources such as solar and wind can reduce dependency on fossil

fuels, which are often heavily imported, leading to a more stable cost structure and greater energy security. This diversification, coupled with risk reduction, is expected to have a positive impact on WACC, supporting economic growth and stability.

While sovereign CDS spreads and WACC highlight the systemic challenges posed by sovereign risk, implementing measures to effectively derisk investments is essential for mitigating financing barriers, particularly in the context of the CB. The CB relies heavily on clean technologies and bio-based solutions, which face unique financing challenges due to high perceived or actual risks, especially in developing economies. To overcome these barriers, cornerstone instruments such as feed-in tariffs, loan guarantees, and blended finance are vital in reducing investment risks and attracting private capital. Policy derisking instruments, such as regulatory reforms and infrastructure improvements, address structural barriers like policy uncertainty and insufficient institutional capacity. Financial derisking instruments, including loan guarantees and public equity co-investments, transfer risks to public entities, enabling investors to access capital at reduced costs. As noted by United Nations Development Program (UNDP), combining policy and financial derisking measures can significantly reduce financing costs for clean energy projects, making them more competitive and scalable (UNDP, 2013). These mechanisms are particularly critical in countries with high sovereign CDS spreads, where elevated risk perceptions can hinder investment flows. By stabilizing the cost of debt and lowering WACC, such instruments can create a favorable investment environment that can foster the growth of CB solutions and enhance their competitiveness against conventional alternatives.

9.5 Conclusion

The transition to CB offers significant potential for increasing sustainability, economic resilience, and social inclusion. By prioritizing regenerative and circular practices, CB challenges traditional extractive models of production and aims to establish economic systems that are inherently compatible with environmental protection and resource efficiency.

However, the competitive landscape for most CB products remains challenging. Established competition from traditional alternatives such as petrochemical-based plastics, fossil fuels, and synthetic fibers creates significant barriers to entry. In particular, these existing products benefit from well-developed infrastructure, economies of scale, and deeply established market systems that have evolved over decades. Thus, the CB enterprises need to strategically use supportive policy frameworks and targeted financial incentives to gain a foothold in the market.

Accordingly, regulatory mechanisms, including subsidies, tax credits, and carbon pricing, can play a pivotal role in leveling the playing field for CB. By reducing production costs and enhancing the financial appeal of sustainable alternatives, these tools can help overcome the economic disadvantages that often characterize early-stage CB initiatives in the market. Furthermore, refining economic metrics,

such as the LCOP, LCOE, or LCOF, to account for the unique features of CB is essential. Incorporating costs offsets from co-products, policy instruments, and derisking measures into the computations not only provides a more realistic assessment of projects' economic viability but also demonstrates how CB can align profitability with sustainability. Additionally, the CB's ability to reduce emissions and increase resource efficiency and local economic resilience underscores its importance in modern sustainability agendas.

A key opportunity for the CB model lies in its ability to generate localized benefits, particularly through the promotion of decentralized production systems. These systems can reduce reliance on large-scale centralized infrastructure and create opportunities for rural and underdeveloped regions. Bioenergy, bioproducts, and cooperative business models illustrate the diverse ways that CB can foster economic resilience and community engagement, adding depth to its value proposition beyond the environmental dimension.

To conclude, the transition to CB presents both challenges and opportunities. Overcoming these challenges requires technological innovation, targeted business models, supporting policy frameworks, and robust economic research to guide decision-making. Detailed economic analysis, including refined cost metrics and derisking strategies, is essential for identifying welfare-enhancing strategies, assessing the economic impacts of policy decisions, and designing financial mechanisms and instruments to encourage the adoption of CB. By aligning economic models with sustainability goals, such research can provide solid insights to overcome barriers to CB initiatives. With well-targeted economic policies and incentives, supportive regulatory frameworks and advances in production technologies, industries can evolve toward regenerative and resource-efficient practices. This transformation will not only reduce environmental damages but also deliver significant long-term socio-economic benefits.

For future research, a long-term policy impact analysis could shed light on which regulatory measures can most effectively support CB growth over time, thus providing guidance for policymakers. On the knowledge front, quantitative evaluations of CB's social and economic impacts such as employment creation and public health improvements can enhance the understanding of its socio-economic contributions. Lastly, refining economic metrics, such as LCOP, LCOE, and LCOF, to account for the unique characteristics of CB is essential. These metrics should incorporate real-world uncertainties, such as fluctuating feedstock costs, policy and regulatory shifts, and evolving financial conditions, which can affect country-specific borrowing costs, and hence, the economic viability of CB initiatives. Finally, because the bioeconomy intrinsically evolves, the transition to a circular bioeconomy is a never-ending process. Future research must embrace these evolving dynamics to ensure that economic and policy decisions are accurate and remain effective over time.

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Chapter 10
Incorporating Circular Bioeconomy into the Sustainable Development of Small Farms in the United States: A Socioeconomic Roadmap

Jie Zhuang, Omayah El-Salim, Jannat Bahanni, Kaitlyn Daniels, Lisa Zottarelli, David Ader, Sara Mulville, and Dilip Nandwani

10.1 Significance of Smallholder Farms

Ninety seven percent of the two million farms are family-owned in the United States (U.S.). They are the backbone of agricultural landscape and food security, contributing 90% of total farm production. Small family farms, which produce no more than $350,000 in annual gross cash farm income (GCFI), account for 89% of all family farms (86% of all farms) (Lim et al., 2024). Small family farms are classified as smallholder farms and are further subdivided into residence farms (with operators retired or having a primary occupation other than farming) and intermediate farms (farming is operator's primary occupation). These smallholder farms often face substantial issues and challenges due to multiple factors such as economic instability

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through limited capital access, fluctuating markets, climate disasters, and the rise and increased competition of industrial agriculture (Litkowski, 2025; USDA--ERS, 2025).

Smallholder farms are significant to rural economy, social equity and sustainability, and local biodiversity (Lowder et al., 2025; Ricciardi et al., 2021). Smallholder farms can play a significant role in ensuring food and nutritional diversities, animal welfare, and local food security in comparison to large-scale farms. More importantly, they conserve critical soil and plant biodiversity and mindfully utilize natural resources. Small farms benefit local communities through the provision of food. As consumer intention shifts with time, many individuals have centered more around sourcing local, fresh, ethical, healthy food, attempting to be more conscientious of environmentally responsible ways to allocate such resources. Opportunities and programs such as community-supported agriculture and farmers markets help small farmers uplift and offer products to local communities. Both farmers and locals benefit from these interactions, with farmers obtaining advanced payment for climate-smart agriculture and customers receiving fresh locally sourced in-season produce (Paul, 2019).

Smallholder farms are also a key element of environmental preservation. For example, smallholder farming systems preserve the biodiversity of local ecosystems, thereby providing better ecosystem services (e.g., ecotourism) to society than large-scale farms. Small farms benefit environmental system by reducing "food miles." Food miles determine the carbon footprint associated with transportation of food products. Most food products sourced locally are from small farm operations, supporting carbon footprint and food mile reduction goals in food production (Stein & Santini, 2022).

The measurement of these indicators must consider the importance of seasonality, animal product consumption reduction, land use practices, production processes, and storage practices. These factors determine the benefits of small farms in the context of sustainability. In general, local food systems work toward environmental sustainability in terms of packaging, locality, and reduction of food loss and waste. Due to the core local aspect of many small farms, the processing and packaging stages and elements of the preparation procedure are significantly lessened (Michaliszyn-Gabryś et al., 2022). Consequently, food loss and waste are reduced with a decrease in mass production and an increase in packaging quality control capacity.

10.2 Challenges of Smallholder Farms

10.2.1 Financial Vulnerabilities

Small farms are facing immense challenges. With modern farming being dominated by industrial-scale operations, small farms must overcome financial strain, lack of access to resources, and limited infrastructure. Within small farms, it is important to consider internal differentiations in GCFI. In 2020, 60% of small farms had a GCFI of less than $10,000. These farms would be considered noncommercial farms. The

GCFI with a range of $10,000–$250,000 is used to distinguish a farming establishment as a small commercial farm (Litkowski, 2025).

According to the report of the United States Department of Agriculture (Lim et al., 2024), small farms (86% of all farms) used 41% of U.S. farmland but generated only 17% of total production value in 2023. Midsize farms (6% of all farms) used 18% of farmland for 18% of total production value. In contrast, large farms (3.5% of all farms) used 31% of the farmland with a contribution of 48% of total production value. These differences suggest that small farms have a large potential in food security and rural economy if infrastructure, financial support, and marketing strategies are improved.

Economic vitality is a major challenge of owning and operating small farms. Operating profit margin (OPM) identifies the share of GCFI that is profitable. OPM conveys the amount of profit a farm can make on each dollar of revenue. It can determine the profitability, cost structure, and overall financial performance of a farming operation. In 2023, 52–85% of small farms, 39% of midsize farms, and 29%–34% of large-scale farms in the United States are in the high-risk zone of financial stability (OPM less than 10%) (Lim et al., 2024).

Another prevailing economic issue for small farms is concerning debt and loan management. Since larger farms require an increased amount of capital, they take out larger loans compared to smaller farms. However, smaller farms accrue larger amounts of debt in relation to their GCFI. The average ratio of debt to GCFI for small "off-farms" farming operations is 22.5, in comparison to a GCFI ratio of 0.4 in "very large" large farms (USDA, 2021). This debt, commonly attributed to purchased land, supplies, and crops, is generated from common lending sources, such as the Farm Credit System, USDA, and commercial banks (Lim et al., 2024).

The above economic pressures lead to financial instability within many small farm households. Small farm operators are shown to undergo more losses from and within their operations than large farms (USDA-ERS, 2025). Overall, 51% of all family farms in the United States had a negative income in 2023. Off-farm occupation family farms lost an average of $3700 while low-sales family farms lost an average of $5700 in 2023 (Lim et al., 2024). The low-sales family farms (GCFI less than $150,000) had the lowest median income ($58,300), compared with very large family farms ($1.02 million) (USDA-ERS, 2025). These income values also account for income that is obtained outside of farming operations, or "off-farm sources," which constitutes over half of the total income amount. Overall, small farms often rely more heavily on off-farm income than larger farms.

10.2.2 Climate Impacts

Climate change drives the occurrence of extreme weather, ecological degradation, resource use, and demographic dynamics, influencing many facets of smallholder farming (Ma & Rahut, 2024). First, climate change makes some communities prone to health-hazards, which are directly linked to natural disasters and environmental

change, such as flooding, wildfire, and air pollution. The recovery of these impacted communities is limited by financial resources and access to food and energy supplies (USEPA, 2025).

Second, climate change conditions lengthen growing seasons, influencing crop production both positively and negatively. Longer growing seasons increase opportunities for farmers to utilize multiple crop cycles or grow long-maturing crops. However, they can also prolong the increasingly severe effects of climate change (USEPA, 2023).

Third, climate change may degrade soil health and productivity. Droughts reduce nutrient use efficiency and threaten crop growth in many regions. With the increasing frequency and severity of heavy storms and floods, soil erosion has caused a depletion of soil nutrients and even relocation of surface fertile soils in agricultural lands. For example, the recent devastation of Hurricane Helene has led to increased erosion in farming operations, as well as the stripping away of nutrients in transportable topsoil in farms primarily in Western North Carolina. This natural disaster decreased soil fertility and thus overall operation output (Gatiboni, 2024). Overall, small farms are impacted much more than large farms. This is due to a lack of resources, finances, and assets to fall back on when handling the aftermath of climate events. This makes the recovery process much more difficult and can lead to both short- and long-term profit loss (FAO, 2014).

10.2.3 Social and Psychological Impacts

With the prevalence of economic and other stresses in smallholder farms, pressure is concentrated on the social aspects inside and outside of farming operations. A social shortcoming associated with small farming is the lack of awareness and educational resources. Based on a survey assessing food safety perceptions within small-scale agricultural operations, gaps are found in facilities, equipment, and materials access. This is specific to food safety rules implemented in southern farmers markets (Doyle et al., 2023). In international settings, harvest ultimately declines with a decreased accessibility to education and the presence of poor management practices (Toillier et al., 2024).

Mental health is a psychological disadvantage that smallholder farmers commonly suffer from. This issue is strongly correlated to economic pressure and other issues plaguing small farms. Legislative and policy shifts such as tariffs have added a layer of strain to the economics of farming operations across the board, regardless of size. As a result, emotional distress becomes more of an issue with the rise of these economic and legislative dilemmas within farming operators. From an international context and perspective, the increase of agribusiness and its subsequent corporatization and globalization are associated with increased farmer stress and suicide as well as a decrease in mental wellbeing. These social issues were strongly linked to the mentioned economic conditions that are unique to smallholder farms (Hagen et al., 2019).

10.3 Circular Bioeconomy as a Multi-Tiered Strategy

Small farms can be revitalized through waste reuse, resource efficiency, and regenerative land management. These practices are subject to the principles of circular bioeconomy. A circular bioeconomy is an economic model that focuses on reducing waste and maximizing the value of renewable biological materials, all while combining biological resources with circular principles to create sustainable systems. There are many core principles involved with circular bioeconomy, such as renewability, waste minimization, sustainability, resource efficiency, and resilience. Renewability deals with plants, animals, microorganisms, and other biological resources being used as raw materials since these are renewable resources. Waste minimization deals with repurposing biowastes and byproducts for cost-reduced or value-added reuse. The sustainability principle focuses on the long-term environmental, social, and economic sustainability through responsible resource use. The resource efficiency principle maximizes the efficiency of biological resources by improving production and consumption processes. The resilience principle advocates the enhancement of natural systems and their functions through practices that regenerate and restore biodiversity of involved ecosystems. In summary, a circular bioeconomy aims to minimize environmental impact by creating closed-loop systems where biological materials are continuously reused.

The adoption of circular bioeconomy systems by smallholder farms requires a multi-tiered strategy, including financial support, infrastructure development, education and training, public awareness initiatives, and policy reform as briefly addressed below.

- **Expanding access to financial support:** The significant up-front cost prevents small farms from adopting circular bioeconomy practices. Small farmers find it risky and struggle to afford new equipment, implement regenerative practices, and obtain certifications. Grants, subsidies, and low-interest loan programs should be established to help small farms overcome these barriers (Pink et al., 2025). With the government and private institutions executing these programs, small farms can engage in new practices, which enhance pest management and soil health, minimize soil disturbing and synthetic fertilizer use, optimize irrigation efficiency, and expand adoptions of drought-tolerant crop varieties, crop rotation, and cover cropping. Other valuable income streams for smallholder farmers could come from carbon credit and ecosystem payment. The practices that increase biodiversity, preserve water resources, and sequester carbon should be compensated. Additionally, the economic burden can be decreased by offering tax incentives for small farms that adopt circular models like those that generate biogas, create bio-based products, or recycle organic waste into fertilizers, since this makes regenerative investments more feasible.
- **Building local infrastructure and markets:** Specialized infrastructure such as facilities for processing composting, biogas generation, or even basic storage and transportation is required for circular bioeconomy to be effective and profitable. Circular bioeconomy is out of reach for many small farms since they lack access

to this specialized infrastructure; therefore, investing in regional cooperatives can help bridge this gap (Berti & Mulligan, 2016). Small farms can pool resources together to share access to equipment, processing centers, and distribution networks, enabling them to compete with larger industrial farms. Local circular systems can also be made by encouraging on-farm bioeconomy models, such as facilities converting waste streams (e.g., manure, food waste, crop residues) into valuable products (e.g., livestock feed, compost, biogas). Circular bioeconomy can help diversify off-farm income by developing value-added products such as regenerative wool, organic produce, or natural biofertilizers, which often yield higher profits. Through startup grants and business development services, these enterprises can be supported and help keep value within local communities by promoting sustainable growth and reducing input costs.

- **Increasing education and training:** Many smallholder farmers are unfamiliar with the tools and techniques required for the transition of conventional farming systems into circular bioeconomy systems. The transition requires a shift not only in methods but also in mindset. Thus, training and technical support from expanded agricultural extension programs like those based at land-grant universities are necessary for building farmers' confidence in adopting circular bioeconomy practices (OECD, 2015). To better serve the rural and underserved areas, mobile outreach programs and field-based learning opportunities should be incorporated to make these resources more accessible. Smallholder farmers can be empowered through training, digital tools, and AI-driven technologies by gaining access to data-informed decision tools like mobile crop diagnostics, precision farming apps, and soil health sensors, as this helps maximize yields, manage risk more effectively, and reduce input. Farmers can learn these modern techniques through school-based agricultural education (e.g., secondary agricultural education), post-secondary education (e.g., community college), and formal certificate programs. In addition, farmer networks can facilitate internal support and peer learning process from niche producers of farm goods.
- **Fostering public awareness and market demand:** Consumer demand is a powerful driver of change. Agricultural literacy in public education on the environment and social benefits of circular bioeconomy is key to creating a market that values smallholder farming. Consumers can make informed choices and support local producers more efficiently through campaigns, workshops, and media initiatives. Government agencies and public institutions should be encouraged to source their food from local farms, as this boosts demand and provides stable markets for small farms. The products can be distinguished by introducing labeling and certification systems. Consumers can support farming systems that align with their values by recognizing labels like "low carbon footprint" or "circular bioeconomy certified" on the product, as this gives small farms a marketing edge. Small farms have massive potential to become leaders in circular bioeconomy with the right support systems in place, such as infrastructure, education, financing, supportive policies, and market visibility (Dhillon & Moncur, 2023). Following the circular bioeconomy principles, these local farms can contribute to

larger climate goals, national food security, and rural revitalization while regenerating their land and communities.

- **Strengthening policy and community engagement**: Integrating circular bioeconomy into agricultural policies such as U.S. Farm Bill is essential to overcoming the challenges that small farms face (Obudzinski, 2016). The circular bioeconomy policies should cover technical assistance, pilot demonstration, stakeholder networking, and research funding. For example, mentorship, cooperative decision-making, and peer learning should be promoted to catalyze farmer-led innovation in circular bioeconomy (Obach & Tobin, 2014).

10.4 Participatory Approaches in Co-design of Solutions

The convergence of goals of farmers and researchers is essential for the design of climate-smart circular bioeconomy solutions for small farms. Circular bioeconomy research should thus be aligned with farming operation goals through participatory approaches including co-creation of knowledge and co-design of solutions. Participatory approaches encourage and necessitate more than simple participation, such as the involvement of knowledge exchange and joint innovation for the purpose of creating an environmentally, economically, and ethically sustainable solution for all parties (Nguyen et al., 2024). Co-creation encompasses the entire process from problem identification to solution implementation, while co-design can be a part of a larger co-creation process with a focus on specific design aspects of the solutions (Melles, 2019). The participatory approaches consider the following specific aspects.

- **Local relevance**: Connecting directly with small-scale farmers for the design and development processes ensures that agricultural solutions are tailored to their circumstances. This fittingness is crucial because it integrates innovations into the cultural context and socioeconomic realities in those communities. Traditional knowledge enhances the practicality of circular bioeconomy practices, adding to their feasibility and long-term sustainability in the community (Pawera et al., 2024).
- **Affordability**: Co-created solutions are usually cheaper than other methods as they consider smallholder farmers' economic challenges. This cooperative approach facilitates the design and implementation of resource-efficient, low-cost technologies that are more likely to be adopted and preserved over time due to their flexibility. Additionally, it is essential for small farms, especially those within vulnerable or marginalized communities, to receive increased financial access for utilizing climate-smart technologies. The technologies should be cost-effective solutions that best fit the needs of small farmers. The affordability can be improved by local resource maximization, microloans or microfinancing, weather indexed insurance, and government grants and subsidies.

- **Accessibility**: Participators collaborate to solve logistical challenges, including inadequate infrastructure, technological access, and local markets. Identifying these challenges allows communities to design and implement better distribution and access strategies through community initiatives addressing local barriers (Touch et al., 2024).
- **Communication and capacity building:** Communications can provoke thoughtful solutions rooted in both local farming experiences and professional knowledge and facilitate their integration for creating and implementing acceptable and sustainable circular bioeconomy solutions. Strategies such as participatory workshops, field school approaches, and demonstrations of expected bioeconomy systems and climate-smart technologies are effective for communication on the adoption of new practices. These strategies facilitate capacity building for participatory design. Training, peer-to-peer learning, and knowledge-sharing can strengthen farmer's confidence in creation and uphold the local community ownership of climate-smart approaches (Hacker et al., 2012). A study on small farms in Kenya found that communications help farmers fully comprehend and understand the new practices and associated technologies. This then encourages them to try the technologies on their farming operations (Waaswa et al., 2021).
- **Feedback loops:** Establishing strong feedback loops through frequent participation aids in continuously improving solutions (Carreno, 2024). Farmers can utilize this to offer real-time data and information so that adjustments can be made on time to enhance the effectiveness and satisfaction with deployed strategies.

10.5 Governance and Institutional Arrangements for Collaboration Between Stakeholders

10.5.1 Multi-Stakeholder Platforms

Understanding the roles of governments, non-governmental organizations (NGOs), local cooperatives, and farmers themselves provides a foundation for discussing effective governance models. Those with a vested interest in the process and production of climate-smart farming initiatives—or stakeholders—can vary vastly. Multi-stakeholder platforms are a foundation for collaborative actions between NGOs, research institutions, farmers, and the private sector. Design by research institutions, implementation by farmers, and support from government agencies and extension services are the three stakeholder sectors in circular bioeconomy. It is crucial to merge the knowledge bases of researchers who deeply understand climate-smart circular bioeconomy, farmers who possess a strong awareness of local ecosystem and environmental factors, and policymakers who can create incentives and coordinate regional trade. With the integration of their perspectives through the multi-stakeholder platforms, the process

of circular bioeconomy implementation can be accessible, affordable, and profitable for small farms. Worth noting is that the most significant stakeholder in the circular bioeconomy initiative is the smallholder farm itself, one of the most impacted stakeholders by climate change.

10.5.2 Decentralized Governance Frameworks

Governance strategies determine how climate-smart solutions are regulated and implemented. The strategies, ranging from policy interventions to grassroots initiatives, shape the operational landscape of climate adaptation efforts in smallholder farming. Decentralized governance structures empower local authorities and communities to take the initiative in implementing and monitoring circular bioeconomy practices that will have the most positive impact on their communities (Martin et al. 2018; Zhuang et al., 2023). From a policy perspective, policies instituted for the purpose of uplifting and improving small farmers should aim to minimize trade-offs, monitor and assess their interactions, and optimize synergies. A critical component of decentralized governance strategies is the development of robust policy and institutional frameworks. These frameworks create an enabling environment for bringing decision-making closer to those most affected by it and enhance their coordination and responsiveness to local needs and priorities while ensuring regulatory compliance and long-term sustainability. Assistance with resource accessibility and circular bioeconomy facilitation is particularly needed for marginalized and vulnerable communities due to limited economic power, social support systems, and credit capacity. Additionally, it is important to document the most successful governance arrangements and share them across regions so that they can be scaled and replicated in differing areas. Securing political commitment and aligning initiatives with national sustainability goals ensures that successes can be expanded and sustained over time (UNESC, 2018).

10.5.3 Legal and Policy Frameworks

Legal and policy frameworks are crucial in defining the roles, rights, and responsibilities of the operation's stakeholders. These frameworks must prioritize disadvantageous groups like smallholder farmers, ensuring that decision-making processes are equitable and participatory (FAO, 2024). Governmental and institutional policies for smallholder farming operations should aim to minimize trade-offs, optimize synergies, and systematically monitor and assess interactions. To achieve this, policy frameworks at local, national, and international levels must be designed to ensure alignment and cooperation across different sectors. On a surface level, it is essential that smallholder farmers are aided in the form of governmental and institutional frameworks. This includes assessments and considerations of farming issues on financial, socioeconomic, policy, and research scales.

10.5.4 Institutional Capacity Building

Building the capacity of institutions at the local level is beneficial for sustaining collaborative efforts. This includes investing in training, funding, and technical support to strengthen regional organizations and enabling them to effectively guide and support the farmers in implementing these strategies (DESA, 2020). Well-structured incentives and funding mechanisms provide farmers with the necessary resources to participate in climate-smart programs effectively. Aligning financial strategies with governance efforts ensures a cohesive approach to sustainable implementation of circular bioeconomy. Providing incentives for farmers can enable the necessary environment for the improvement of operations. Employing certain mechanisms relating to financial improvement can provide incentives to smallholder farmers to control barriers that normally inhibit their ability to utilize elements of climate-smart circular bioeconomy. Incentives can be policy-driven, voluntary, or institutionally driven. Forms of incentives can include payments for ecosystem services, carbon credit usage, and microloan and credit management. In addition to governance and financial support, market accessibility remains a key factor. A well-regulated trade environment enhances the viability of climate-smart solutions by ensuring fair pricing, reliable market access, and support for climate-conscious agricultural products.

Though direct action and applicability of circular bioeconomy principles to climate-smart agriculture are imperative to the success of smallholder farmers, current market and buyer availability is an important factor to consider in terms of success (Li et al., 2024). Larger-scale commercial farms depend on wholesale markets and supermarket supply chain networks to support financial gain and overall profitability. However, smallholder farmers typically experience a much lower and less consistent product volume output. A few small direct channels to markets have been discussed, such as community-supported agriculture programs, farmers markets, and direct-to-retail (Dimitri & Gardner, 2019). These programs are beneficial and accessible, but their profitability and returns are low. Intergenerational income, off-farm income, and credit and insurance are three main sources of income and financial support for small farmers. Intergenerational income is highly dependent on personal circumstances and situations and is often not reliable and not wholly sufficient. Off-farm income sources are necessary for most small farmers, constituting the major source of small farmer income (Lim et al., 2024). Finally, credit and insurance shape United States agriculture structure and thus become a significant income source for small farms.

Soil health is critical for the success of crop growth and consequently final supply for profit purposes. Increased and optimal soil health levels largely determine the sustainability and profitability of ecological low-based small farms. Soil health can take years to build up through a variety of sustainable agricultural methods, and it can greatly contribute to the long-term fertility boosting, carbon sequestration, input cost decreases, and more. In these ways, up-front capital is a critical means of investing in soil health.

These primary income sources considered with small farms draw to the conclusion that small farms are disadvantaged in the realm of financing farming operations. This combined with the disincentivization and underestimation of sustainable farming practices by federal crop insurance programs, and negligible direct government payment funds enhance said disadvantage. Some of these financial issues can be tackled on a policy-scale through several ways or outlets. For example, as a large portion of financial stress often stems from farm equipment acquisition, government agencies and community-driven initiatives have worked toward alleviating this (USDA, 2024).

10.6 Strategies for Circular Bioeconomy Implementation

10.6.1 Financial Support

Socioeconomic conditions, such as land tenure security, income levels, and access to markets, significantly impact the implementation of circular bioeconomy solutions (Touch et al., 2024). Financial barriers generally cover financial circumstances and farm profit correlated to size and specifically includes labor needs and costs, investment costs, and access to credits. These barriers can be overcome through several solutions. Methods such as financial incentives and support mechanisms can help ease the barriers for low-income farmers and encourage their adoption of climate-smart circular bioeconomy practices. For example, existing USDA programming, such as the Microloan Program and Regional Conservation Partnership Program (RCPP), can provide small farms with financial assistance in operations. The Microloan Program specifically assists small and midsize farms through granting them access to loans of up to $50,000 by way of a simplified application process (USDA, 2021; 2024). The RCPP stimulates the adoption of conservation strategies on smallholder farms (Adusumilli, 2019; Agricultural Act, 2014). Additionally, USDA provides a few other financial assistance programs, such as the Conservation Reserve Program (CRP), Climate-Smart Agriculture Innovative Finance Initiative, and Partnerships for Climate-Smart Commodities. All of these are centered around expanding markets for small farms in climate-smart commodities and innovating effective finance mechanisms to accelerate climate-smart practice uptake by farmers, especially those in marginalized and vulnerable communities. Along with adaptive approaches and complementary tools like agricultural insurance, these programs also support the application of circular bioeconomy practices on small farms. Other partnerships aiding the implementation of climate-smart circular bioeconomy can include the Environmental Defense Fund (EDF), Farm Credit, and American Farmland Trust (AFT). These partnerships offer financing and expertise for farmers to implement conservative, sustainable, and circular practices (USDA, 2025).

10.6.2 Policy Support

Agricultural policy is key to the transformation of smallholder farming systems into circular bioeconomy systems. Current policy barriers within small farming communities include lacking clarity and awareness of policy details, unclear accountability for policy regulators, and weak support from policy holders/makers (Guynn et al., 2024). Solutions to these barriers include increased information dissemination, policy award and decision standardization, and awareness of program or policy resources. In terms of information dissemination, farmers often complain about not knowing or having no easy access to important program information, such as deadlines, qualifications, application processes, and general awareness. These problems could be reduced through web-based platforms, printed materials, and through direct communication (text, email, phone call, etc.). Another proposed solution is to make a catalog of programs to enhance the ease with which farmers can educate themselves on program and policy details in the decision-making process. Farmers might feel a heavy sense of favoritism from program awarders and policymakers, specifically toward larger farms (Guynn et al., 2024; OVBC, 2023). To fix this, standardization of the awarding process, clearly defining an application review and acceptance process, and providing feedback on denied applications can be beneficial for farmers who plan to apply or reapply for different programs. Additionally, policies and well-structured incentive systems, including subsidies and sharing schemes, can create an enabling and trusting environment for change. These measures help reduce the perceived risks associated with adopting new technologies or practices.

10.6.3 Institutional Support

Institutional support from areas such as extension services, cooperatives, and local governments provides critical guidance and resources throughout the implementation process of circular bioeconomy solutions. Sustained support ensures that farmers have long-term assistance, improving the durability and lasting impact of interventions. Additionally, continuous monitoring and flexible implementation strategies allow for responsive changes based upon farmer feedback and environmental conditions. Adaptive management practices can enhance the resilience and long-term success of food–water–energy systems (Ma & Rahut, 2024).

10.6.4 Technical Support

Technical design plays an important role in the adoption of new practices at affordable costs. Circular bioeconomy solutions must be simple, user-friendly, and compatible with small farming methods currently instilled or affordable if established.

Scalable technologies that require minimal disruption to traditional workflows are more likely to be embraced by farmers. Additionally, environmental suitability must also be a core design consideration. Solutions should be tailored to local climate patterns, water availability, cropping system, and soil conditions.

10.7 Conclusions

Small farms play a pivotal role in benefiting local communities environmentally, economically, and socially. Their core challenges are directly affiliated with economic vulnerability, climatic disasters, and psychosocial repercussions. To overcome these issues, small farmers, researchers, government organizations, and other large stakeholders need to take part in participatory co-design approaches, specifically for implementing realistic, acceptable, and sustainable solutions. Financially and politically, it is important to build a new framework centered around the co-design process. Circular bioeconomy is such a framework that can converge actions and transform small farms into competitive smart systems that are resilient to various challenges.

To ensure the future viability and adoption of climate-resilient, circular bioeconomy systems in smallholder farming, we suggest evidence-based interventions, such as institutional reforms, financial mechanisms, and knowledge co-production. In the long run, the integration of smallholder needs into circular bioeconomy frameworks must be recognized not as a sectoral concern, but as a foundational, cross-sectoral requirement for scalable sustainability of the food system. The future of small farming must transcend resource preservation to provide irreplaceable economic values for both on-farm and off-farm incomes, nutrition diversification, and ecosystem services through forming circular bioeconomy communities.

10.8 Disclaimer

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Chapter 11
Alternative Bioeconomy Strategies for Decarbonization

Yanyou Guan, Gordon Rausser, David Zilberman, and Elliot Choi

11.1 Introduction

The global economy faces a critical climate challenge with potentially catastrophic costs. Under current emission trajectories, global temperatures could rise by 3.2 °C by 2100, more than double the Paris Agreement's 1.5 °C target, triggering economic losses of $32–133 trillion globally (Swiss Re Institute 2021; Kahn et al., 2021). The United States alone could face GDP losses up to $21 trillion, while agricultural systems worldwide confront yield declines and increased vulnerability (Hsiang et al., 2017).

While renewable energy technologies have achieved remarkable cost reductions and could create 42 million jobs by 2050 (IRENA, 2020), wind and solar power alone cannot eliminate fossil fuel dependence by 2050. Renewable deployment faces fundamental constraints: intermittency issues, grid integration challenges, and hard-to-electrify sectors including heavy industry, shipping, and aviation. The timeline required to completely replace fossil fuels through renewable substitution exceeds the window available to prevent catastrophic climate impacts.

This gap has intensified focus on carbon sequestration strategies that can actively remove atmospheric CO_2 while providing bio-based alternatives for sectors that cannot easily electrify. Unlike renewable energy substitution, carbon sequestration delivers negative emissions, reducing existing atmospheric CO_2 rather than simply avoiding new emissions.

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A diverse portfolio of decarbonization strategies has emerged, ranging from renewable energy deployment and carbon capture and storage to biotechnological approaches (Rausser et al., 2024). Each strategy contributes essential capabilities toward the ambitious goal of achieving net-zero emissions by 2050. The scientific consensus emphasizes that no single technological solution possesses the scale or versatility to address the full complexity of the climate crisis; instead, success demands a carefully orchestrated combination of complementary approaches that leverage different mechanisms, timescales, and economic drivers (IPCC, 2018).

Within this strategic landscape, bioeconomy strategies for decarbonization have emerged as particularly compelling options, distinguished by their capacity to deliver multiple co-benefits while addressing climate objectives. These strategies have attracted increasing attention from policymakers, investors, and researchers due to their inherent environmental sustainability, demonstrated potential for economic viability using existing infrastructure and supply chains. Unlike purely technological solutions that often require extensive new infrastructure development, many bioeconomy approaches can build upon established agricultural, forestry, and industrial systems while creating new economic opportunities in rural and industrial communities.

Bioeconomy strategies for decarbonization encompass a broad spectrum of economic activities that harness the carbon-processing capabilities of biological systems. These approaches utilize diverse biogenic resources, including terrestrial plants, marine organisms, microorganisms, and algae, to actively sequester carbon dioxide from the atmosphere or industrial flue gases. The captured carbon is then transformed and stored in various long-term carbon reservoirs, including forest biomass, soil organic matter, durable bio-based materials, and geological formations coupled with bioenergy systems (Yaashikaa et al., 2023; Dees et al., 2023). This biological foundation provides inherent advantages in terms of sustainability, renewability, and integration with natural carbon cycles.

The significance of bioeconomy strategies extends beyond their direct carbon mitigation potential. These approaches offer unique opportunities to address multiple sustainability challenges simultaneously, including biodiversity conservation, soil health improvement, rural economic development, and reduction of dependence on fossil-based materials. Furthermore, many bioeconomy strategies can provide negative emissions, actively removing CO_2 from the atmosphere rather than simply avoiding new emissions, a capability that climate models increasingly identify as essential for meeting ambitious temperature targets.

However, the bioeconomy landscape for decarbonization is characterized by significant heterogeneity in terms of technological maturity, economic readiness, and implementation requirements. While some strategies have achieved commercial deployment and market penetration, others remain in early research phases with uncertain pathways to scale. This diversity necessitates careful analysis of each approach's current status, potential contribution, and development needs to inform strategic investment and policy decisions.

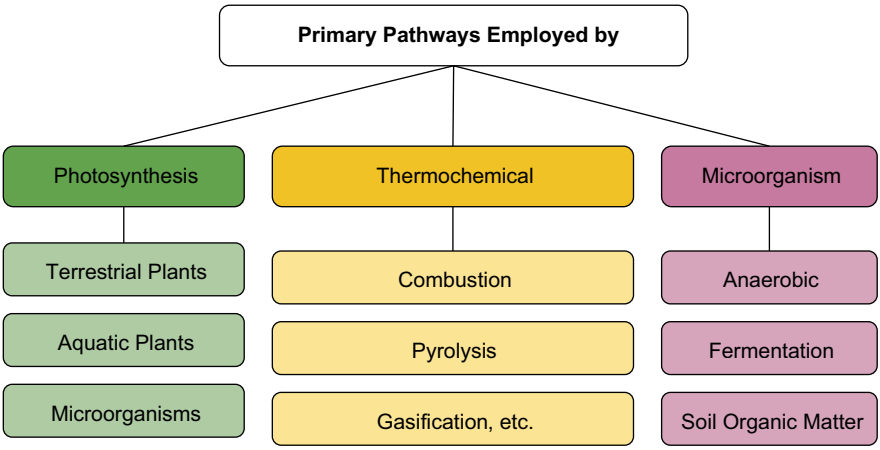
This chapter provides a comprehensive analysis of bioeconomy strategies for decarbonization, progressing from fundamental mechanisms to practical implementation considerations. We begin by examining the primary pathways through which

these strategies achieve carbon mitigation and then classify the main categories of technologies including carbon sequestration and storage, carbon substitution, and carbon removal approaches. We assess technology readiness levels and economic feasibility across different strategies, concluding with recommendations for accelerating bioeconomy contributions to global decarbonization efforts through strategic investment, policy frameworks, and regionally tailored implementation approaches.

11.2 Primary Pathways of Bioeconomy Strategies for Decarbonization

Bioeconomy strategies achieve decarbonization through three fundamental and interconnected pathways: photosynthesis, thermochemical processes, and microbial processes. These pathways represent engineered applications of natural processes that the biosphere has employed for billions of years to absorb atmospheric CO_2, transform it into biomass, and store it in various carbon reservoirs. The elegance of bioeconomy approaches lies in their ability to harness and optimize these time-tested natural mechanisms while adapting them to meet contemporary decarbonization needs.

The interconnected nature of these pathways becomes apparent when examining natural carbon cycling processes. Plants capture atmospheric CO_2 through photosynthesis, generating biomass that can subsequently undergo transformation into fuels such as methane and ethanol through microbial activity, or decompose into stable soil organic matter that enhances long-term carbon storage. Over geological timescales, biomass buried under sedimentary layers undergoes natural thermochemical conversion processes that ultimately produce fossil fuel deposits such as coal and natural gas. Modern bioeconomy strategies essentially replicate and dramatically accelerate these natural processes through carefully designed engineered interventions, compressing geological timescales into industrially relevant timeframes while maintaining the fundamental carbon transformation mechanisms.



11.2.1 Photosynthesis: The Foundation of Biological Carbon Capture

Photosynthesis represents the foundational biological process that underpins virtually all bioeconomy decarbonization strategies. Through this remarkable process, plants, algae, and certain photosynthetic bacteria harness solar energy to convert atmospheric carbon dioxide and water into glucose, which serves as the primary building block for biomass formation.

In most bioeconomy strategies, photosynthesis functions as the critical initial step that generates the diverse feedstocks required for downstream processing through thermochemical or microbial conversion pathways. The biomass produced through photosynthesis can be directly utilized for energy generation through combustion, or it can serve as the raw material for sophisticated biorefinery processes that yield a wide array of products including advanced biofuels, industrial chemicals, bioplastics, and other value-added bio-products.

The efficiency and scale of photosynthetic carbon capture can be enhanced through various approaches, including the selection of high-productivity plant species, optimization of growing conditions, genetic improvements to photosynthetic pathways, and the development of integrated production systems that maximize land use efficiency. These enhancements represent active areas of research and development that could significantly expand the carbon capture potential of photosynthesis-based bioeconomy strategies.

11.2.2 Thermochemical Processes: Transforming Biomass Through Controlled Heat Applications

Thermochemical processes encompass a suite of technologies that convert biomass into energy-rich products through the controlled application of heat, often coupled with catalytic reactions. These processes produce valuable outputs including power, heat, advanced fuels, synthesis gas, bio-oil, and biochar through various forms of thermal decomposition. The versatility of thermochemical conversion makes it applicable to virtually any form of biomass feedstock, from agricultural residues to dedicated energy crops to organic waste streams.

Combustion represents the most straightforward thermochemical process, involving the direct burning of biomass in the presence of oxygen to produce heat that can be utilized for industrial processes or converted to electricity through steam turbines. While combustion is technologically mature and widely deployed, its carbon neutrality depends on sustainable biomass sourcing and the displacement of fossil fuel alternatives.

Pyrolysis operates through a more sophisticated mechanism, subjecting biomass to thermal decomposition at elevated temperatures, typically ranging from 400 to 1000 °C, in an oxygen-free environment. This controlled heating process breaks

down complex biomass molecules into three primary product streams: bio-oil (a liquid fuel precursor), biochar (a stable carbon-rich solid), and syngas (a gaseous mixture containing carbon monoxide, hydrogen, methane, and other compounds) (Vamvuka, 2011). The relative proportions of these products can be controlled through process parameters, allowing optimization for specific applications and market demands.

Gasification extends the thermochemical processing concept by partially oxidizing biomass at even higher temperatures, typically between 700 and 1400 °C, with carefully controlled but limited oxygen supply. This process primarily produces syngas composed predominantly of carbon monoxide and hydrogen, which can serve as a versatile intermediate for producing synthetic fuels, chemicals, or electricity through fuel cells (Kirubakaran et al., 2009). The high-quality syngas produced through gasification can be converted into a wide range of products through established chemical processes, making it a valuable pathway for replacing petroleum-derived chemicals and fuels.

A critical consideration for thermochemical processes involves their carbon balance implications. While these conversion technologies can produce valuable renewable energy and materials, they also release the captured carbon back into the atmosphere during conversion or subsequent use. Therefore, achieving net-negative or truly low-carbon outcomes requires coupling thermochemical processes with carbon capture and storage (CCS) technologies that can intercept and permanently sequester the CO_2 emissions. This integration, often referred to as bioenergy with carbon capture and storage (BECCS), represents one of the most promising pathways for achieving negative emissions at scale.

11.2.3 Microbial Processes: Harnessing Biological Catalysts for Carbon Transformation

Microbial processes leverage the remarkable metabolic diversity and efficiency of microorganisms to convert biomass and even direct CO_2 streams into valuable fuels, chemicals, and soil amendments (Hu et al., 2025). These biological conversion pathways utilize bacteria, yeasts, fungi, and microalgae as living catalysts that can perform complex chemical transformations under relatively mild conditions compared to thermochemical processes. The specificity and efficiency of microbial systems often exceed what can be achieved through conventional chemical catalysis, while operating at ambient temperatures and pressures that reduce energy requirements.

Anaerobic digestion exemplifies the power of microbial consortiums working in oxygen-free environments to break down complex organic matter into simpler compounds. This process, which occurs naturally in environments such as wetlands and sediments, has been optimized for industrial applications to generate biogas composed primarily of methane and carbon dioxide. The methane can be captured and

used directly as a renewable fuel for heating, electricity generation, or vehicle fuel, while the remaining digestate serves as a nutrient-rich soil amendment that can enhance soil carbon storage and fertility.

Fermentation processes represent another crucial category of microbial conversion, utilizing specific microorganisms to transform biomass-derived sugars into valuable products including bioethanol, organic acids, and specialty chemicals. The fermentation pathway has achieved significant commercial success in producing bioethanol from corn, sugarcane, and other feedstocks, demonstrating the scalability and economic viability of microbial conversion technologies. Advanced fermentation systems are expanding beyond traditional ethanol production to generate a broader range of chemicals and materials that can substitute for petroleum-derived products.

Direct microbial conversion represents an emerging frontier where specialized microorganisms can convert CO_2 directly into liquid fuels, bioplastics, or other valuable compounds without requiring biomass intermediates. These processes, sometimes called "artificial photosynthesis" or "electrofuels," utilize engineered microorganisms that can fix CO_2 using electrical energy or other non-photosynthetic energy sources. While still in early development stages, direct microbial conversion holds significant promise for creating carbon-negative production processes that actively remove CO_2 from the atmosphere while generating commercial products.

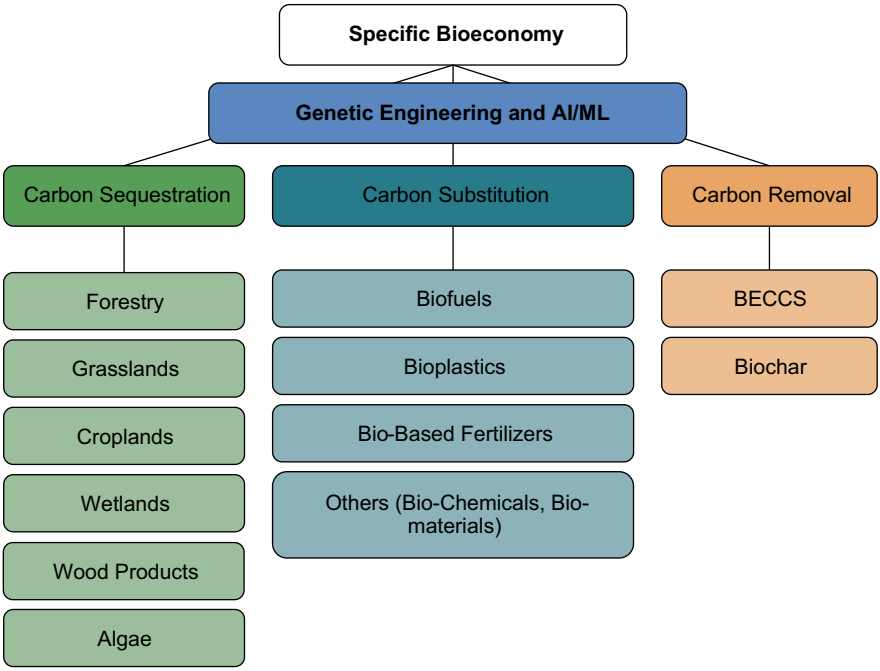
Soil-based microbial processes play an important role in carbon sequestration strategies by enhancing the formation and stability of soil organic matter. Beneficial soil microorganisms contribute to carbon storage through multiple mechanisms: they can directly incorporate carbon into their biomass, facilitate the formation of stable soil aggregates that protect organic matter from decomposition, and support enhanced plant growth through nitrogen fixation and phosphate solubilization. These soil microorganisms essentially act as biological engineers that can transform agricultural and forestry systems into more effective carbon sinks while simultaneously improving soil health and productivity.

The integration of these microbial pathways creates opportunities for comprehensive bio-based production systems that not only generate alternatives to fossil fuels and petrochemicals but also contribute to circular carbon management by enhancing soil health and ecosystem services (Yaashikaa et al., 2023). The versatility and efficiency of microbial systems position them as critical components of sustainable bioeconomy strategies that can deliver both carbon mitigation and economic value.

11.3 Specific Bioeconomy Strategies for Decarbonization

The diverse landscape of bioeconomy strategies for decarbonization can be organized through various taxonomic approaches, though significant overlaps often exist across different categorization schemes. To provide clarity and systematic

understanding, we classify these strategies into three functional groups based on their primary roles in the decarbonization process: carbon sequestration and storage, carbon substitution, and carbon removal. This functional classification recognizes that many individual strategies contribute to multiple outcomes simultaneously, creating synergistic effects that enhance their overall decarbonization potential.



11.3.1 Carbon Sequestration and Storage

Land-based and aquatic vegetation systems, encompassing grasslands, croplands, wetlands, and forests, represent nature's primary mechanism for removing atmospheric carbon through photosynthesis and storing it in both plant biomass and soil organic matter. These natural carbon capture systems store carbon in multiple compartments including leaves, stems, trunks, root systems, and the complex soil matrix where microbial activity plays a crucial role in carbon stabilization. Strategic management and enhancement of these ecosystems can dramatically amplify their inherent carbon sequestration capacity, making them essential components of comprehensive decarbonization strategies.

Forestry: Maximizing Woody Biomass Carbon Storage

Forests rank among the most important terrestrial carbon sinks on Earth, storing vast quantities of carbon in both above-ground woody biomass and below-ground soil systems. The carbon storage capacity of forests is supported and enhanced by complex networks of soil microorganisms that facilitate nutrient cycling and carbon stabilization processes. Forest-based decarbonization strategies focus on expanding forest coverage and optimizing forest management practices to maximize long-term carbon storage.

Afforestation involves the deliberate establishment of new forests on lands that have not previously supported forest ecosystems, effectively creating new carbon sinks where none existed before. This strategy can transform degraded agricultural lands, abandoned industrial sites, or other non-productive areas into productive carbon storage systems. Reforestation focuses on replanting or facilitating natural regeneration of forests on lands that previously supported forest ecosystems but have been cleared or degraded through human activities or natural disturbances. Both afforestation and reforestation play critical roles in climate change mitigation by enhancing global forest carbon storage capacity while providing additional ecosystem services including biodiversity conservation, watershed protection, and rural economic opportunities (Ménard et al., 2023).

The effectiveness of forest-based carbon sequestration depends on several factors including species selection, site conditions, management practices, and long-term sustainability planning. Fast-growing species can rapidly accumulate carbon in the short term, while slower-growing species often provide more stable, long-term carbon storage. Mixed-species forests typically demonstrate greater resilience to environmental stresses and may provide more stable carbon storage over extended periods compared to monoculture plantations.

Grasslands: Underground Carbon Powerhouses

Grassland ecosystems employ a fundamentally different carbon sequestration strategy compared to forests, primarily storing carbon below ground in extensive root systems and soil organic matter. This below-ground carbon storage approach offers distinct advantages, including greater protection from disturbances such as fire, drought, or grazing pressure. Microbial communities in grassland soils play essential roles in processing root exudates and decomposing organic matter, ultimately contributing to the formation of stable soil carbon pools (Bai & Cotrufo, 2022).

Effective grassland management for carbon sequestration centers on practices that promote deep root development and soil organic matter accumulation. Rotational and adaptive grazing systems involve periodically moving livestock across different pasture areas, allowing grazed areas to recover and promoting deeper root growth that enhances soil carbon storage. This management approach mimics natural grazing patterns and can stimulate plant productivity while building soil carbon reserves.

Prescribed burning represents another important grassland management tool that, when properly implemented, can enhance carbon sequestration capacity. These controlled fires reduce accumulated dry biomass, stimulate new root system development, and promote soil carbon storage processes. Additionally, prescribed burning helps prevent large-scale wildfires that can release significant quantities of stored carbon back to the atmosphere. The timing, frequency, and intensity of prescribed burns must be carefully managed to optimize carbon benefits while maintaining ecosystem health.

Wetlands: Efficient Carbon Traps

Wetland ecosystems function as highly effective carbon sinks due to their unique anaerobic, waterlogged conditions that dramatically slow the decomposition of organic matter. The permanently saturated soils in wetlands create oxygen-limited environments where decomposition processes operate much more slowly than in well-drained terrestrial systems. Simultaneously, the high plant productivity characteristic of many wetland systems enables rapid atmospheric carbon uptake through photosynthesis, creating a combination of high carbon input and low carbon loss that results in substantial net carbon accumulation (Were et al., 2019).

The carbon sequestration capacity of wetlands can be enhanced through both direct management interventions and support for natural processes. Wildlife populations, ecosystem engineers such as beavers, contribute significantly to wetland carbon storage by constructing dams and other structures that expand wetland areas and improve water retention capacity. These natural modifications increase the total area of carbon-sequestering wetland habitat while enhancing the long-term stability of water levels that maintain anaerobic conditions essential for carbon preservation.

Strategic wetland management for carbon sequestration focuses on avoiding drainage of existing wetland areas, which can rapidly release stored carbon through accelerated decomposition under aerobic conditions. Equally important is the rewetting of degraded wetland areas that have been previously drained for agriculture or development. Restoration of these degraded systems can rapidly re-establish their carbon sink functions while providing additional ecosystem services including flood control, water quality improvement, and biodiversity habitat.

Croplands: Transforming Agriculture into Carbon Storage

Agricultural systems present significant opportunities for carbon sequestration through the implementation of management practices that enhance soil organic matter accumulation while maintaining or improving agricultural productivity. With appropriate management interventions, croplands can transition from carbon sources to significant carbon sinks, providing climate benefits while supporting food security objectives.

Reduced tillage and no-tillage farming practices represent foundational strategies for agricultural carbon sequestration. These approaches minimize mechanical soil disturbance, which slows the decomposition of soil organic matter and creates conditions that favor carbon accumulation. Traditional intensive tillage breaks up soil aggregates and exposes organic matter to oxygen, accelerating decomposition and carbon loss. By reducing or eliminating tillage operations, farmers can enhance soil carbon storage while often reducing fuel consumption and labor requirements (Lessmann et al., 2022).

Cover cropping involves planting non-harvested crops during periods when fields would otherwise remain bare, such as between growing seasons or as understory plants in perennial systems. These cover crops continue photosynthetic carbon capture during periods when main crops are not growing, while their roots and above-ground biomass contribute organic matter to soil carbon pools. Cover crops also support diverse soil microbial communities that facilitate carbon stabilization processes, prevent soil compaction that can limit root growth, and provide additional ecosystem services including erosion control and nutrient retention.

Rice cultivation presents unique carbon management challenges and opportunities due to the anaerobic conditions created by field flooding. Mid-season drainage of flooded rice fields introduces oxygen into previously anaerobic soils, stimulating populations of methanotrophs. This practice can reduce methane emissions from rice systems by 30 to 50 percent while maintaining rice yields (Tang et al., 2019). Complementary practices such as straw removal further reduce anaerobic decomposition and limit methane production from agricultural residues.

Additional effective practices for agricultural carbon sequestration include agroforestry systems that integrate trees and shrubs into agricultural landscapes, creating additional woody biomass carbon storage while providing shade, windbreaks, and additional income sources for farmers. Diverse crop rotations enhance soil health and increase system resilience while often improving carbon storage through varied root systems and residue inputs that support different microbial communities. These integrated approaches to agricultural carbon management demonstrate that climate benefits and agricultural productivity can be achieved simultaneously through thoughtful system design and management.

Wood Products: Extended Carbon Storage Through Material Use

Wood-based materials utilized in construction, furniture manufacturing, and other long-lived applications function as medium-term carbon storage systems that lock captured atmospheric carbon away for decades or even centuries. The carbon storage duration depends on the specific application, with structural building materials typically providing longer storage periods than products with shorter service lives. Beyond their direct carbon storage function, wood products provide important indirect climate benefits by displacing more carbon-intensive materials such as cement, steel, and petroleum-based plastics, thereby reducing the lifecycle emissions associated with construction and manufacturing activities (Evans et al., 2022).

The climate benefits of wood products depend critically on sustainable forest management practices that ensure ongoing carbon sequestration and regeneration of harvested biomass. Sustainable forestry systems maintain forest carbon storage capacity over time by balancing harvest rates with forest growth, while often enhancing overall forest health and resilience. Well-managed forest systems can provide a continuous supply of wood products for carbon storage applications while maintaining and potentially expanding forest-based carbon sinks.

The effectiveness of wood products as a carbon storage strategy can be enhanced through design approaches that maximize product lifespan, facilitate material reuse and recycling, and optimize the displacement of high-carbon alternative materials. Additionally, end-of-life management strategies that direct wood waste toward long-term storage applications or bioenergy with carbon capture can extend the carbon benefits beyond the initial product use phase.

Algae Cultivation: High-Efficiency Aquatic Carbon Capture

Algae cultivation systems, encompassing both microscopic microalgae and larger macroalgae species, represent a promising decarbonization strategy distinguished by exceptional carbon capture efficiency and minimal competition with terrestrial resources. Algae demonstrate remarkably rapid growth rates that enable high rates of atmospheric carbon capture per unit area and time, often exceeding the carbon capture rates achievable through terrestrial plant systems. Equally important, algae cultivation systems do not compete with arable land resources, making them compatible with food security objectives and terrestrial conservation priorities (Sarwer et al., 2022).

Algae can be cultivated through various production systems designed to optimize growth conditions and carbon capture efficiency. Photobioreactor systems provide controlled environments that maximize algae productivity through optimized light delivery, nutrient management, and harvesting protocols. Open pond systems offer lower capital costs and simpler operation while still achieving substantial carbon capture rates. Marine cultivation systems can utilize ocean resources for large-scale algae production without requiring freshwater or terrestrial land resources.

The versatility of algae biomass creates opportunities for integrated production systems that maximize both carbon capture and economic value. Harvested algae can be processed into biofuels that displace fossil fuel consumption, converted into soil amendments that enhance terrestrial carbon sequestration, transformed into bioplastics that replace petroleum-based materials, or utilized as high-protein feed ingredients for livestock or aquaculture systems. This versatility enables algae cultivation systems to contribute to circular bioeconomy approaches that optimize resource utilization while maximizing carbon benefits across multiple applications.

11.3.2 Carbon Substitution

Bioeconomy-based carbon substitution strategies harness the fundamental biological processes of photosynthesis, thermochemical conversion, and microbial transformation to produce bio-based alternatives that can directly replace fossil-derived products across multiple economic sectors. These substitution approaches encompass a diverse portfolio of products including biofuels, bioplastics, and bio-fertilizers that provide functionally equivalent performance to their petroleum-based counterparts while significantly reducing lifecycle carbon emissions. The growing sophistication of these strategies is enhanced by emerging technologies including genetic engineering techniques that optimize organism performance and artificial intelligence and machine learning (AI/ML) systems that improve productivity, efficiency, and economic viability throughout the production process.

Biofuels: Renewable Energy from Biological Resources

The biofuel sector encompasses a comprehensive range of renewable energy carriers produced from diverse biomass feedstocks including corn, sugarcane, soybeans, agricultural residues, and forestry waste materials. These feedstocks can be converted through various pathways into multiple fuel products including bioethanol, biodiesel, biogas, sustainable aviation fuel (SAF), bio-oil, and bio-methanol. While biofuel production systems do require carbon-intensive inputs such as fertilizers, agricultural machinery, and processing energy, comprehensive lifecycle analyses consistently demonstrate that biofuels achieve net carbon reduction compared to fossil fuels. This carbon benefit stems from the fundamental principle that CO_2 emissions during biofuel combustion originate from biomass that had previously captured atmospheric carbon through photosynthesis, creating a closed carbon cycle rather than releasing geologically sequestered carbon (Khan et al., 2021).

Bioethanol represents one of the most widely deployed biofuels, commonly derived from starch-rich and sugar-rich crops such as corn and sugarcane through established microbial fermentation processes. This biofuel has achieved significant market penetration through blending programs with conventional gasoline and plays an increasingly important role in transportation sector decarbonization. However, the reliance on food crops for bioethanol production creates potential competition with food production systems for limited arable land resources, raising concerns about food security and land use sustainability.

Advanced bioethanol production pathways address these concerns by utilizing cellulosic feedstocks including agricultural residues, forestry waste materials, and dedicated energy crops such as switchgrass and miscanthus. These cellulosic sources do not compete directly with food production and can often utilize marginal lands unsuitable for food crops. Additionally, microalgae present a promising alternative feedstock due to their high starch and sugar content, exceptionally rapid

growth rates, and complete non-competition with terrestrial food production systems (Niphadkar et al., 2018).

Biodiesel production primarily relies on vegetable oils, animal fats, and used cooking oils that undergo transesterification, a well-established chemical reaction between triglycerides and short-chain alcohols, typically methanol, in the presence of catalysts such as sodium hydroxide or potassium hydroxide. This process operates under relatively mild conditions of 50 to 65 °C and yields both biodiesel and glycerol, with the latter serving as a valuable co-product for various industrial applications. The biodiesel sector is experiencing significant innovation through the advances of microalgae cultivation systems and development of lipid-rich algae strains, which can achieve much higher oil yields per unit area compared to traditional oilseed crops (Sharma et al., 2012).

Sustainable aviation fuel represents a critical decarbonization technology for the aviation sector, which faces unique challenges in transitioning to low-carbon energy sources due to the energy density requirements of aircraft propulsion. SAF can be produced from diverse sustainable feedstocks including waste oils, agricultural and forestry residues, and even captured CO_2 through sophisticated thermochemical or microbial conversion pathways. Advanced SAF production systems can achieve lifecycle greenhouse gas emission reductions of up to 80% compared to conventional jet fuel, making them essential for aviation industry decarbonization goals (Ng et al., 2021).

Biogas production utilizes anaerobic digestion processes to convert organic materials including agricultural waste, sewage sludge, and dedicated energy crops into a methane-rich gas mixture. The resulting biogas typically contains 50% to 75% methane along with carbon dioxide and trace compounds, and can be utilized directly for heating applications or converted to electricity through combustion in specialized generators. Biogas systems provide the additional benefit of processing organic waste streams that might otherwise decompose and release methane to the atmosphere, creating both renewable energy and waste management solutions (Sawyerr et al., 2019).

Bio-oil production employs advanced thermochemical processes including pyrolysis and hydrothermal liquefaction to convert biomass feedstocks such as forestry and agricultural residues into liquid fuel precursors. The resulting bio-oil can undergo upgrading through hydrotreating processes that increase energy density and improve fuel properties, enabling blending with conventional petroleum fuels or utilization as a standalone renewable fuel. These technologies provide pathways for converting low-value biomass residues into high-value liquid fuels (Wang et al., 2022).

Bio-methanol serves as a renewable alternative to fossil-derived methanol, which is an important industrial chemical and potential transportation fuel. Bio-methanol can be produced through two primary technological pathways. The first approach involves biomass gasification to produce synthesis gas (syngas) containing hydrogen, carbon monoxide, and carbon dioxide, which is then catalytically converted to methanol under high pressure and moderate temperature conditions. The second pathway utilizes biogas or biomethane reforming to generate syngas, which is subsequently processed into methanol through established catalytic synthesis processes (Gautam et al., 2020).

Bioplastics: Renewable Alternatives to Petroleum-Based Polymers

The bioplastics sector encompasses a diverse array of polymer materials that can replace conventional petroleum-based plastics while reducing fossil fuel dependence and associated carbon emissions. It is important to note that the term "bioplastics" encompasses two distinct but sometimes overlapping categories: bio-based plastics derived from renewable biomass or captured CO_2, and biodegradable plastics that can be decomposed by microorganisms regardless of their origin. For the purposes of decarbonization analysis, this discussion focuses specifically on bio-based plastics, which contribute to carbon mitigation through fossil fuel substitution and reduced lifecycle carbon footprints rather than through end-of-life biodegradation characteristics (Nandakumar et al., 2021).

Starch-based plastics represent one of the most commercially developed categories of bioplastics, utilizing starch extracted from corn, potatoes, and other starch-rich agricultural crops. The production process involves gelatinization of starch granules followed by plasticization with appropriate additives to achieve desired mechanical properties and processability. These materials can be formulated to achieve a wide range of properties suitable for applications including packaging films, disposable tableware, and agricultural mulch films (Do Val Siqueira et al., 2021).

Cellulose-based plastics utilize the world's most abundant natural polymer as a renewable feedstock for plastic production. Cellulose derived from wood pulp, cotton linters, or other plant sources undergoes chemical modification to form cellulose esters or ethers, which are then plasticized to create thermoplastic materials with biodegradable characteristics. The abundance and renewability of cellulose feedstocks make these materials attractive for large-scale applications (Molenveld & Slaghek, 2022).

Aliphatic polyester bioplastics encompass a sophisticated family of polymers including polyhydroxyalkanoates (PHA), polylactic acid (PLA), polybutylene succinate (PBS), and polycaprolactone (PCL). These versatile materials can be produced from sugars, starches, plant oils, or even captured CO_2 through various production pathways including fermentation, polycondensation, and ring-opening polymerization. The diversity of production methods and feedstocks enables optimization for specific applications and local resource availability (Hillmyer & Tolman, 2014).

Protein-based plastics utilize both plant proteins, such as those derived from soybeans, and animal proteins, including casein from milk, as renewable polymer feedstocks. These materials are typically produced through crosslinking and thermal processing techniques that create polymer networks with useful mechanical properties. Protein-based plastics often exhibit excellent barrier properties and can be formulated for applications including food packaging and agricultural films (Grewell et al., 2014).

Lignin-based plastics represent an innovative approach to utilizing lignin, a complex aromatic polymer that is generated as a byproduct of pulp production and ethanol manufacturing processes. Lignin can be incorporated as a filler material in

composite formulations or chemically modified to create polymer networks with unique properties. Advanced processing techniques can depolymerize lignin into aromatic monomers that can be utilized in conventional plastic manufacturing processes, creating pathways for converting waste lignin into valuable polymer products (Zhang et al., 2024).

Chitin-based plastics utilize chitin, a naturally occurring polymer found in crustacean shells, fungal cell walls, and insect exoskeletons. Chitin can be processed into chitosan, a versatile biopolymer with unique properties including antimicrobial activity and biocompatibility. The abundance of chitin in waste streams from seafood processing and the potential for insect farming create opportunities for converting waste materials into valuable polymer products (Zhou et al., 2022).

The development of bioplastics continues to advance through innovations in feedstock utilization, processing technologies, and material properties optimization. These advances are expanding the range of applications where bioplastics can effectively replace conventional petroleum-based polymers while providing superior environmental performance and contributing to circular economy principles through the utilization of renewable and waste-derived feedstocks.

Bio-Based Fertilizers: Harnessing Microbial Partnerships for Sustainable Agriculture

Bio-based fertilizers represent a sophisticated approach to agricultural nutrition that leverages the natural symbiotic relationships between specific microorganisms and plants to enhance nutrient availability and uptake. These biological systems utilize specialized microorganisms that colonize either the rhizosphere (the soil region immediately surrounding plant roots) or the internal tissues of plants themselves, where they enhance the supply or accessibility of essential nutrients including nitrogen, phosphate, and potassium. This biological approach to plant nutrition provides a sustainable alternative to conventional fossil-based fertilizers by utilizing living systems to deliver nutrients through natural biological processes rather than through direct chemical application.

The mechanisms through which bio-based fertilizers operate demonstrate the elegance of biological nutrient cycling systems. Nitrogen-fixing bacteria exemplify this approach by establishing colonies in the plant rhizosphere where they convert atmospheric nitrogen gas (N_2) into ammonia (NH_3) through the enzyme nitrogenase. This biologically fixed ammonia is subsequently converted by other soil microorganisms into nitrate, a readily bioavailable form of nitrogen that plant roots can efficiently absorb and utilize for protein synthesis and growth (Mus et al., 2016). This biological nitrogen fixation process eliminates the need for energy-intensive industrial nitrogen fixation that characterizes conventional fertilizer production.

Similarly, phosphate-solubilizing bacteria provide essential phosphorus nutrition by converting insoluble inorganic phosphate compounds naturally present in soils into soluble phosphate ions that become accessible for plant root absorption. This microbial activity effectively mobilizes phosphorus that would otherwise remain

unavailable to plants, reducing the need for phosphate fertilizer inputs while improving phosphorus use efficiency in agricultural systems (Billah et al., 2019). These biological processes not only provide plant nutrition but also improve soil health through enhanced microbial diversity and biological activity.

Bio-based fertilizers can be formulated into various physical forms including liquid suspensions, powder formulations, and granular products to facilitate application using existing agricultural equipment and practices. The development of stable, effective formulations requires careful attention to maintaining microbial viability during storage and application while ensuring consistent performance across diverse soil and climate conditions.

Insect frass fertilizer represents an innovative category of bio-based fertilizer that utilizes the waste products of insect farming operations. This fertilizer consists of insect excrement from species such as black soldier fly larvae and mealworms, combined with uneaten portions of their feed and shed exoskeletons. The resulting product provides a balanced nutrient profile rich in nitrogen, phosphorus, and potassium, making it an effective substitute for conventional fossil-based fertilizers. The development of insect farming for various applications creates opportunities for circular economy approaches that convert organic waste into valuable protein, oil, and fertilizer products (Poveda, 2021).

11.3.3 Carbon Removal: Achieving Negative Emissions Through Biological Systems

Carbon removal bioeconomy strategies encompass advanced approaches that combine biological carbon capture with permanent storage technologies to achieve net-negative emissions. These strategies leverage the fundamental processes of photosynthesis, thermochemical conversion, and microbial transformation to extract atmospheric CO_2 and prevent its return to the atmosphere through various storage mechanisms. Unlike carbon substitution strategies that primarily avoid emissions by replacing fossil fuels, carbon removal approaches actively reduce atmospheric CO_2 concentrations, making them essential components of climate mitigation scenarios that seek to limit global temperature increases.

Bioenergy with Carbon Capture and Storage (BECCS): Negative Emissions Energy Systems

Bioenergy with carbon capture and storage represents one of the most promising large-scale carbon removal technologies, combining renewable energy production with permanent CO_2 storage. BECCS systems begin with the production of various forms of bioenergy including bio-heat, bio-power, and biofuels from diverse biomass feedstocks through established thermochemical and microbial conversion

processes. The key innovation of BECCS lies in preventing the atmospheric release of CO_2 that was originally captured and sequestered in biomass during plant growth.

The carbon capture component of BECCS systems employs various technological approaches including solvent absorption, solid adsorption, and chemical looping combustion to capture CO_2 emissions from bioenergy production and utilization processes. Solvent absorption systems use chemical solvents to selectively remove CO_2 from flue gas streams, while solid adsorption technologies employ porous materials to physically capture CO_2 molecules. Chemical looping combustion represents an advanced approach that inherently separates CO_2 during the combustion process, producing a concentrated CO_2 stream suitable for capture and storage.

Following capture, the concentrated CO_2 stream undergoes compression and transportation to suitable geological storage sites including depleted oil and gas wells, deep saline aquifers, and other stable geological formations. The permanent storage of this biogenic CO_2 creates a net-negative emissions process that actively removes atmospheric carbon while providing renewable energy services. The scalability of BECCS systems makes them attractive for achieving the large-scale carbon removal requirements identified in climate stabilization scenarios.

Biochar: Stable Carbon Storage Through Controlled Pyrolysis

Biochar production represents a carbon removal strategy that creates stable, long-term carbon storage while generating valuable soil amendment products. Biochar is a charcoal-like, carbon-rich material produced primarily through pyrolysis of biomass feedstocks under controlled high-temperature, low-oxygen conditions. While other thermochemical processes such as gasification can also yield biochar, pyrolysis optimization specifically for biochar production achieves much higher yields and superior carbon storage characteristics compared to alternative production methods.

The carbon sequestration value of biochar stems from its exceptional stability and resistance to decomposition. This carbon-rich material can store carbon for periods ranging from hundreds to thousands of years, effectively removing atmospheric CO_2 on timescales relevant to climate stabilization goals. The aromatic carbon structures formed during pyrolysis create chemically stable compounds that resist biological and chemical degradation processes that would otherwise return carbon to the atmosphere.

Beyond its primary function as a carbon storage medium, biochar provides significant value as a soil amendment that can enhance agricultural productivity and soil health. Biochar applications improve soil water retention capacity, enhance nutrient retention and availability, and promote improved soil structure through enhanced aeration and aggregate formation. These soil health benefits can improve crop yields and reduce fertilizer requirements, creating economic incentives for biochar adoption while delivering climate benefits (Hunt et al., 2010).

The dual benefits of carbon storage and soil improvement position biochar as an attractive carbon removal strategy that can provide immediate economic returns to

farmers while contributing to long-term climate goals. The development of sustainable biochar production systems that utilize agricultural and forestry residues can create circular economy approaches that convert waste materials into valuable carbon removal and soil improvement products.

11.3.4 Emerging Technologies: Genetic Engineering and Artificial Intelligence

The continued advancement of bioeconomy decarbonization strategies increasingly depends on sophisticated emerging technologies that can enhance and optimize biological systems for carbon mitigation applications. Genetic engineering and artificial intelligence/machine learning (AI/ML) represent two powerful technological tools that, when combined, create synergistic effects that can unlock the full decarbonization potential of bioeconomy approaches. These technologies enable the optimization of biological systems beyond their natural capabilities while providing the analytical tools necessary to understand and control complex biological processes.

Genetic Engineering: Optimizing Biological Carbon Processing

Genetic engineering encompasses sophisticated molecular biology techniques that involve modifying the DNA of organisms to alter their characteristics and functions, thereby enhancing their efficiency and capacity for carbon sequestration, conversion, and utilization. These approaches enable the development of biological systems that exceed the performance limitations of naturally occurring organisms while maintaining the fundamental advantages of biological carbon-processing systems.

Research efforts in genetic engineering for enhanced carbon sequestration focus on improving photosynthesis efficiency in crops and trees to enable greater atmospheric CO_2 uptake and storage. Advanced genetic modifications can optimize the biochemical pathways of photosynthesis, reduce photorespiration losses, and enhance the overall carbon fixation capacity of plants (Kirschbaum, 2011). Complementary approaches focus on engineering enhanced root systems with increased biomass and deeper penetration depths that enable greater soil carbon storage capacity and improved nutrient and water uptake efficiency (Chen et al., 2018).

Agricultural applications of genetic engineering emphasize increasing the yield and quality of food crops and dedicated bioenergy feedstocks to enhance the economic viability and carbon efficiency of bioeconomy systems. Higher-yielding crops can provide more biomass for conversion to biofuels and other bio-products

while reducing the land area required for feedstock production, thereby minimizing competition with food production and natural ecosystems.

Microalgae genetic engineering represents a promising frontier for enhancing biofuel production and direct CO_2 capture systems. Research efforts focus on modifying algae strains to improve their CO_2 uptake efficiency, enabling more effective direct carbon capture from atmospheric or industrial sources. Simultaneously, genetic modifications can increase lipid content and optimize fatty acid profiles to enhance biofuel yields and quality (Gupta et al., 2024). These enhanced algae systems can potentially achieve carbon capture and biofuel production rates that exceed those possible with naturally occurring strains.

Artificial Intelligence and Machine Learning: Accelerating Biological Optimization

Artificial intelligence and machine learning technologies provide powerful computational and analytical capabilities that can dramatically accelerate genetic engineering processes while enabling real-time optimization of complex bioprocesses. These technologies complement genetic engineering by providing the analytical tools necessary to understand, predict, and control the behavior of modified biological systems (Zhao et al., 2022).

AI algorithms can analyze vast datasets of genetic sequences, metabolic pathways, and phenotypic outcomes to predict optimal genetic modifications for achieving specific performance targets such as maximum photosynthesis rates, highest crop yields, or deepest root development. Machine learning systems can identify complex relationships between genetic modifications and organism performance that would be difficult or impossible to discern through traditional experimental approaches, thereby accelerating the development of improved biological systems.

Real-time process optimization represents another critical application of AI/ML technologies in bioeconomy systems. Machine learning algorithms can analyze continuous data streams from fermentation bioreactors, including parameters such as temperature, pH, dissolved oxygen levels, and metabolite concentrations, to predict optimal operating conditions for maximum product yields and minimum energy consumption. These predictive control systems can automatically adjust process parameters to maintain optimal conditions throughout production cycles, improving both economic and environmental performance.

The integration of AI/ML with genetic engineering creates feedback loops that enable iterative improvement of biological systems. Machine learning analysis of performance data from genetically modified organisms can inform subsequent rounds of genetic modifications, creating a directed evolution process that rapidly optimizes biological systems for specific applications. This combined approach represents a transformative technology platform that can unlock the full potential of biological systems for decarbonization applications.

11.4 Technology Readiness and Economic Feasibility

The transformative potential of bioeconomy strategies for decarbonization can only be realized when their underlying technologies achieve sufficient maturity and demonstrate economic feasibility that enables widespread implementation across diverse markets and applications. These two fundamental criteria, namely technological readiness and economic viability, serve as critical determinants for the successful deployment and scaling of bioeconomy approaches. Without adequate technological maturity, promising strategies remain confined to laboratory settings or small-scale demonstrations, while economically unviable technologies face insurmountable barriers to market adoption regardless of their technical performance. This section provides a comprehensive assessment of both technology readiness levels and economic feasibility across the full spectrum of bioeconomy decarbonization strategies.

11.4.1 Technology Readiness Level

The technology readiness level (TRL) framework provides a systematic and widely accepted methodology for evaluating the maturity of emerging technologies across various development stages. Originally developed by the National Aeronautics and Space Administration (NASA) in the 1990s to assess aerospace technologies, the TRL framework has been adapted and refined for application across diverse technological domains including energy, environmental, and biotechnology sectors. The framework employs a nine-point scale where TRL 1 represents the earliest conceptual stage and TRL 9 indicates full commercial deployment and operational maturity.

The Electric Power Research Institute (EPRI) has adapted this framework specifically for energy technologies, defining three distinct development phases that correspond to the nine TRL levels (see Table 11.1). The research phase encompasses TRL 1 through 3, covering basic principles observation, technology concept formulation, and analytical and experimental critical function proof of concept. The development phase spans TRL 4 through 6, including component and system validation in

Table 11.1 Technology readiness level (TRL)

TRL 1	Basic principles observed, initial concept	Research
TRL 2	Formulation of the application	
TRL 3	Proof-of-concept tests, component level	
TRL 4	System validation in a laboratory environment	Development
TRL 5	Sub-system validation in a relevant environment	
TRL 6	Fully integrated pilot tested in a relevant environment	
TRL 7	Sub-scale demonstration, fully functional prototype	Demonstration
TRL 8	Commercial demonstration, full-scale deployment in final form	
TRL 9	Normal commercial service	

Freeman and Bhown (2011)

laboratory and relevant environments. Finally, the demonstration phase covers TRL 7 through 9, encompassing system prototype demonstration, system complete and qualified, and actual system proven in an operational environment (Freeman & Bhown, 2011) (Table 11.1).

Bio-Carbon Sequestration: Mature Practices and Emerging Innovations

The technology readiness landscape for bio-carbon sequestration strategies reflects the diverse nature of approaches within this category, ranging from well-established land management practices to cutting-edge biotechnology applications. This technological diversity creates significant variations in TRL across different carbon sequestration approaches, with some strategies ready for immediate large-scale deployment while others remain in early research phases.

Most conventional carbon sequestration and storage strategies demonstrate high technological maturity and widespread global implementation. Effective management practices for forestry systems, including afforestation, reforestation, and sustainable forest management, represent fully mature technologies (TRL 9) with established protocols, proven effectiveness, and extensive operational experience across diverse climate zones and forest types. Similarly, cropland management practices such as reduced tillage, cover cropping, and crop rotation have achieved full technological maturity through decades of agricultural research and practical application.

Wetland management and restoration strategies also demonstrate high TRL ratings, with well-established techniques for wetland protection, restoration, and enhancement that have been successfully implemented across various geographic and ecological contexts. Wood products for carbon storage represent another mature application area where established forestry and manufacturing practices enable effective long-term carbon sequestration through durable wood products in construction and other applications.

In contrast, microalgae cultivation for carbon sequestration occupies the mid-range TRL spectrum, typically ranging from TRL 3 to 8 depending on the specific cultivation approach and application context. Laboratory-scale microalgae systems have demonstrated proof of concept for high-rate carbon capture, while pilot-scale facilities have validated technical feasibility under controlled conditions. However, challenges remain in scaling these systems to commercial size while maintaining economic viability and technical performance (Deprá et al., 2024).

Genetic engineering approaches aimed at enhancing photosynthesis efficiency or increasing root depth for improved soil carbon storage represent the earliest stage of technological development, typically operating at TRL 1 to 3. These approaches involve fundamental research into plant biology and genetic modification techniques, with most work still occurring in laboratory settings. While promising results have been achieved in controlled environments, significant research and development efforts are required to translate these innovations into field-ready applications.

Biofuels: Established Industries and Advanced Development

The biofuel sector demonstrates the most diverse TRL landscape among bioeconomy strategies, with technology readiness levels spanning the complete range from TRL 1 to 9. This diversity reflects both the maturity of established biofuel industries and the continued innovation in advanced biofuel production technologies.

Conventional biofuel technologies have achieved full technological maturity (TRL 9) and support substantial global industries. Bioethanol production from food crops such as corn and sugarcane through established fermentation processes represents a fully mature technology with extensive commercial deployment, standardized production processes, and well-developed supply chains. Similarly, biodiesel production from vegetable oils, animal fats, and used cooking oils through transesterification processes has reached commercial maturity with widespread global implementation (Cantarella et al., 2023).

Biomethane production through anaerobic digestion of organic materials also demonstrates full technological maturity, with thousands of operational facilities worldwide processing agricultural waste, sewage sludge, and dedicated energy crops. These established biofuel technologies benefit from decades of operational experience, refined production processes, and supportive policy frameworks that have enabled their successful market penetration.

Advanced biofuel technologies occupy the development and demonstration phases, typically ranging from TRL 4 to 8 as they undergo scaling and optimization for commercial deployment. Cellulosic ethanol production represents a prominent example of this category, with several demonstration-scale facilities operating globally while technical and economic challenges are addressed to enable widespread commercialization. Bio-methanol production through biomass gasification and methanol synthesis, bio-oil production via pyrolysis, and biobutanol production through advanced fermentation processes similarly demonstrate mid-range TRL ratings as they progress through pilot and demonstration phases (Cantarella et al., 2023; Dębowski et al., 2022; Vuppaladadiyam et al., 2023).

Algal biofuel production presents particular challenges that have limited its progression through the TRL scale despite significant research investments. Despite significant efforts and investments by developers, scaling algae cultivation from laboratory and pilot systems to commercial production remains technically challenging, keeping the technology in the developmental phase with TRLs typically ranging from 4 to 6.

Genetic engineering applications for enhanced biofuel production represent emerging strategies operating at TRL 1 to 4, focusing on developing modified organisms with improved fuel production characteristics. These approaches require substantial additional research and development before progressing to demonstration and commercial phases.

Sustainable aviation fuel (SAF) production encompasses multiple technological pathways that exhibit varying TRL ratings from 4 to 9 depending on the specific production route and feedstock. Established pathways using conventional feedstocks and proven conversion technologies demonstrate higher TRL ratings, while novel production routes utilizing advanced feedstocks or conversion processes operate at lower TRL levels (Watson et al., 2024).

Bioplastics: Commercial Success and Innovation Pipeline

The bioplastics sector demonstrates significant technological diversity with TRL ratings ranging from 3 to 9, reflecting both successful commercial products and ongoing innovation in novel bioplastic materials and production processes. This technological landscape encompasses well-established commercial bioplastics alongside emerging materials that promise enhanced performance or sustainability characteristics.

Several bioplastic technologies have achieved full commercial maturity (TRL 9) with substantial market presence and established supply chains. Starch-based bioplastics, bio-polyethylene terephthalate (bio-PET), bio-polyethylene (bio-PE), and polylactic acid (bio-PLA) represent mature technologies with proven manufacturing processes, consistent product quality, and growing market adoption across various applications including packaging, consumer goods, and automotive components (Börner & Zinn, 2024).

Other bioplastic technologies are approaching commercialization with TRL ratings of 7 to 9, indicating successful demonstration and early commercial deployment. Cellulose-based bioplastics such as cellulose acetate for cigarette filters and cellophane for packaging applications have demonstrated commercial viability in specific market segments. Polybutylene succinate (PBS) and polybutylene adipate terephthalate (PBAT) have achieved demonstration-scale production and are entering commercial markets with growing application portfolios.

Polyhydroxyalkanoate (PHA) production presents an interesting case study in technology development, with conventional production methods using pure microbial cultures and refined sugar feedstocks achieving higher TRL ratings (7–9) while novel production approaches utilizing mixed microbial cultures with wastewater or captured CO_2 as feedstocks operate at lower TRL levels (3–4). This variation reflects ongoing innovation efforts to improve the economics and sustainability of PHA production through alternative feedstocks and production processes.

Bio-Based Fertilizers: Established Applications and Emerging Innovations

Bio-based fertilizer technologies span TRL ratings from 4 to 9, reflecting both well-established commercial applications and emerging innovations in biological nutrient delivery systems. The variation in technology readiness levels corresponds to differences in scientific understanding, production complexity, and market development across different types of bio-based fertilizers.

Nitrogen-fixing fertilizers have achieved full technological maturity (TRL 9) with widespread commercial deployment and established agricultural applications. These products utilize well-understood biological nitrogen fixation processes and have been successfully integrated into agricultural production systems worldwide (Wen et al., 2021). The commercial success of nitrogen-fixing fertilizers reflects decades of research into plant–microbe interactions and the development of stable, effective microbial inoculant products.

Phosphate-solubilizing fertilizers and insect frass fertilizers represent emerging technologies in the development stage, typically operating at TRL 4 to 6. These technologies have demonstrated proof of concept and technical feasibility but require additional development work to optimize production processes, ensure consistent performance, and establish market acceptance (Y. Cheng et al., 2023; Poveda, 2021). The lower TRL ratings reflect ongoing research into microbial ecology, production optimization, and field application protocols.

Bioenergy with Carbon Capture and Storage (BECCS): Integrated System Maturity

BECCS technologies present a unique assessment challenge because they integrate multiple established technologies including bioenergy production and carbon capture and storage systems. The overall TRL for BECCS applications depends on the maturity of constituent technologies and their successful integration into cohesive systems. Generally, most BECCS strategies demonstrate high technological readiness with TRL ratings of 7 to 9, reflecting the maturity of underlying bioenergy and CCS technologies and successful demonstration of integrated systems (Möllersten & Raza, 2022).

Specific BECCS applications demonstrate varying levels of technological maturity based on the complexity of integration and operational experience. Biomass power with CCS, bioethanol with CCS, biodiesel with CCS, and biomethane with CCS typically achieve TRL ratings of 8 to 9, indicating successful demonstration and early commercial deployment. These applications benefit from the high maturity of underlying bioenergy technologies and established CCS approaches that can be readily integrated.

Waste-to-energy with CCS generally operates at TRL 6 to 7, reflecting successful pilot-scale demonstrations while technical and economic optimization continues. Biohydrogen with CCS represents a less mature application at TRL 4 to 6, requiring additional development work to optimize hydrogen production processes and integration with CCS systems.

Biochar: Approaching Commercial Maturity

Biochar production and application represents a highly mature technology with TRL ratings of 8 to 9, indicating successful demonstration and approaching widespread commercialization. The high technology readiness level reflects extensive research into pyrolysis processes, biochar characterization, and agricultural applications that have established technical feasibility and operational protocols (Rex et al., 2024).

The maturity of biochar technology enables immediate deployment for carbon sequestration and soil improvement applications, though continued development focuses on optimizing production processes, standardizing product quality, and expanding market applications. The approaching commercial maturity of biochar

positions it as a readily implementable carbon removal strategy that can provide both climate and agricultural benefits.

11.4.2 Economic Feasibility

The widespread adoption and transformative impact of any decarbonization strategy fundamentally depend on its economic viability. Economic feasibility serves as the critical determinant between theoretical potential and practical implementation at scale. For carbon sequestration and removal technologies, this viability is typically quantified through carbon capture costs expressed in dollars per ton of CO_2 ($/T CO_2). In contrast, carbon substitution strategies are evaluated by comparing the levelized production costs of alternative bio-products against their fossil-based counterparts. This economic landscape reveals considerable variation across different bioeconomy approaches, with some strategies demonstrating immediate commercial readiness while others remain economically prohibitive despite their technical promise.

Bio-Carbon Sequestration: Cost-Effective Natural Solutions

Bio-carbon sequestration strategies demonstrate superior economic performance compared to mechanical direct air capture (DAC) technologies, which carry estimated capture costs ranging from $300–1000 per ton of CO_2. Within the bio-sequestration portfolio, afforestation and reforestation emerge as the most economically attractive options, with exceptionally low costs estimated between $4.2–16.9 per ton of CO_2 (Morkovina et al., 2023). These nature-based solutions leverage existing ecological processes, minimizing technological infrastructure requirements while delivering substantial carbon benefits.

Cropland management practices, including no-till or reduced-till farming and cover cropping, present a credible economic proposition. These strategies not only reduce operational costs and improve agricultural yields but also generate additional revenue streams through carbon credit markets. This triple benefit of cost reduction, productivity enhancement, and revenue generation positions sustainable agriculture as a cornerstone of economically viable decarbonization.

Wetland conservation and restoration present a more complex economic picture. While wetland protection represents a cost-effective approach to maintaining existing decarbonization capacity, restoration projects demand significantly higher investment. Current estimates place wetland restoration costs between £105–5883 per hectare (Walia, 2024), reflecting the substantial effort required to rehabilitate degraded ecosystems.

At the opposite end of the economic spectrum, microalgae cultivation for carbon sequestration faces formidable cost challenges, with estimates reaching $800–1600 per ton of CO_2 (Wilson et al., 2014). These elevated costs reflect the intensive

technological requirements and energy inputs necessary for large-scale algae production systems.

A critical challenge across all bio-sequestration strategies involves monitoring, reporting, and verification (MRV) of sequestered carbon. This is acute for forestry, cropland, and wetland management, where natural variability and long-term carbon stability create complex measurement and verification requirements that add to overall project costs.

Biofuel Economics: Bridging the Cost Gap

The economic landscape for biofuels reveals a spectrum of competitiveness relative to fossil fuels. Conventional biofuels, including corn ethanol, sugarcane ethanol, and biodiesel, have achieved relative cost parity with fossil-based fuels, with production costs estimated at $1.13–3.48 per gallon. This competitive positioning has enabled their integration into existing fuel markets and policy frameworks.

However, advanced biofuels face more significant economic hurdles. Cellulosic ethanol production carries break-even minimum selling prices ranging from $0.9–6.00 per gallon, depending on feedstock selection and processing technologies (Aui et al., 2021). This wide range reflects the sensitivity of production economics to technological choices and operational scale, with costs often exceeding those of fossil fuel production.

Algae-based biofuels encounter even steeper economic challenges, with production costs running 100–200% higher than conventional biofuels (Muthuraman & Kasianantham, 2023). Similarly, sustainable aviation fuel (SAF) faces substantial cost premiums, averaging at least 120% more expensive than fossil-based jet fuel (Watson et al., 2024). These cost differentials highlight the need for continued technological advancement and supportive policy frameworks to achieve economic viability.

Bioplastics: Premium Pricing for Sustainable Alternatives

The bioplastics sector currently operates in a premium pricing environment relative to conventional petrochemical plastics. Traditional fossil-based plastics such as PVC, polypropylene (PP), and polyethylene terephthalate (PET) typically cost between $0.8–5.0 per kilogram. In comparison, bio-PET production costs approximately €2.25 per kilogram, representing about a 30% premium over fossil-based PET (Montava-Jordà et al., 2019).

Among bioplastic alternatives, bio-polylactic acid (PLA) demonstrates the most favorable economic profile, with production costs approaching those of conventional plastics. This cost competitiveness has positioned bio-PLA as a leading commercial bioplastic, in packaging applications where the premium can be justified by sustainability benefits.

Bio-Fertilizers: Long-Term Value Despite Higher Initial Costs

Bio-fertilizers present a cost-effective case for long-term economic value despite higher upfront costs. While initial purchase prices typically exceed those of synthetic fertilizers, bio-fertilizers deliver enhanced agricultural yields, improved soil health, and greater environmental sustainability. These benefits translate into superior long-term economic returns compared to fossil-based fertilizers, though the higher initial investment can present adoption barriers for cost-sensitive agricultural operations (Daniel et al., 2022).

Carbon Removal Technologies: BECCS and Biochar Economics

Bioenergy with carbon capture and storage (BECCS) technologies demonstrate significantly more favorable economics than mechanical direct air capture systems (Zohdi, 2024). Bioethanol plants with carbon capture showcase attractive cost profiles, with carbon capture costs typically ranging from $15–35 per ton of CO_2 due to the high purity of CO_2 in fermentation emissions (Congressional Budget Office 2023). This low-cost carbon capture opportunity reflects the inherent advantages of biological processes that naturally concentrate CO_2.

Biomass power plants and waste-to-energy facilities with carbon capture present moderate costs, ranging from €45–125 per ton of CO_2, with variation depending on the specific carbon capture technology employed (Beiron et al., 2022).

Biochar production through pyrolysis offers an attractive economic proposition by providing dual benefits: atmospheric CO_2 removal and valuable co-product generation, including syngas and bio-oil. With biochar pricing around $800 per ton, the carbon removal cost of pyrolysis biochar ranges between $46–250 per ton of CO_2 (Cheng et al., 2021). This cost range positions biochar as significantly more economical than direct air capture while generating marketable products that can offset production costs.

Economic Implications for Implementation Strategy

The economic analysis reveals a hierarchy of implementation priorities based on cost-effectiveness. Nature-based solutions, afforestation and reforestation, offer immediate economic viability and should form the foundation of near-term decarbonization strategies. Conventional biofuels and selected bioplastics like bio-PLA present opportunities for market-ready substitution in specific applications.

Advanced technologies such as algae-based fuels, SAF, and most bioplastics require continued technological development and supportive policy environments to achieve economic competitiveness. However, the carbon removal potential of BECCS and biochar production presents opportunities for integration into comprehensive decarbonization portfolios, when carbon pricing mechanisms adequately value their climate benefits.

Specific strategy	Technology readiness level	Economic feasibility
Bio carbon sequestration and storage		
Afforestation and reforestation	9	$4.2–16.9/T CO2
Grassland, cropland, wood product	8–9	NA
Wetland	8–9	£105–5883/ha
Micro algae cultivation	3–8	$800–1600/T CO2
Genetic engineering & AI/ML	1–6	NA
Carbon substitution		
Biofuel	**1–9**	
Conventional biofuel	9	$1.13–3.48/gallon
Cellulosic biofuel	4–8	$0.9–6.00/gallon
Algal biofuel	4–8	100–200% more expensive than fossil-based jet fuel on average
Sustainable aviation fuel	4–9	120% more expensive than fossil--based jet fuel on average
Bioplastic	**3–9**	
Bio-PET, bio-PE, bio-PLA	9	$0.8–5/kg
PBS, PBAT	7–9	NA
PHA	3–9	NA
Bio fertilizer	**4–9**	**NA**
Genetic engineering and AI/ML	**1–4**	**NA**
Carbon removal		
BECCS	**4–9**	
Biomass power with CCS and waste to energy with CCS	7–9	€45–125/T CO2
Biofuel with CCS	6–7	$15–35/T CO2
Biochar	**8–9**	**$46–250/T CO2**

11.5 Conclusion

Bioeconomy strategies for decarbonization offer a multifaceted approach to achieving carbon neutrality by 2050, uniquely combining climate action with environmental health improvements and sustainable development objectives through three primary pathways, namely photosynthesis, thermochemical processes, and microbial processes. These strategies encompass carbon sequestration and storage, carbon substitution, and carbon removal approaches that harness natural biological systems for climate mitigation.

The technology maturity landscape reveals significant diversity across bioeconomy strategies. Well-established approaches including forestry management, conventional biofuels, and starch-based bioplastics have achieved commercial maturity

(TRL 9) with proven economic models and widespread deployment. Advanced technologies such as BECCS and cellulosic ethanol occupy the critical development phase (TRL 4-8), demonstrating technical feasibility while working toward cost competitiveness. Emerging innovations including genetic engineering for enhanced photosynthesis and advanced algal systems remain in early research stages (TRL 1-3) but offer transformative potential for future applications.

Economic feasibility varies dramatically across strategies, creating a clear implementation hierarchy. Nature-based solutions like afforestation and reforestation offer exceptional cost-effectiveness at $4.2–16.9 per ton CO_2, while conventional biofuels have achieved cost parity with fossil alternatives. However, advanced technologies including algae-based fuels, sustainable aviation fuel, and most bioplastics face significant cost premiums that require continued technological development and supportive policy frameworks.

Future research priorities should focus on several critical areas. Advanced genetic engineering approaches need fundamental research to enhance photosynthesis efficiency, optimize root systems for soil carbon storage, and improve feedstock yields. Artificial intelligence and machine learning applications require development to accelerate genetic engineering processes and optimize bioprocess operations. Economic research must address cost reduction pathways for advanced biofuels and bioplastics, while policy research should evaluate optimal carbon pricing mechanisms and regulatory frameworks that incentivize bioeconomy deployment.

Scaling challenges represent another crucial research frontier, particularly for algae cultivation systems, cellulosic ethanol production, and BECCS integration. Life cycle assessment studies are needed to optimize environmental benefits across different bioeconomy strategies, while supply chain research must address sustainable feedstock sourcing and logistics optimization. Additionally, interdisciplinary research should explore bioeconomy cluster development that maximizes synergies between different strategies and regional implementation approaches that leverage local resource endowments.

The successful deployment of bioeconomy strategies requires coordinated investment spanning research institutions, private sector engagement through targeted incentives, and robust carbon pricing mechanisms that create economic value for carbon services. Regional implementation strategies must recognize diverse local advantages, with forest-rich regions emphasizing land-based sequestration, industrialized areas focusing on waste-to-energy systems, and coastal regions developing marine bioeconomy applications.

As these technologies mature and scale, their role will likely expand beyond direct carbon benefits to include grid balancing, material security, and food system resilience, positioning the bioeconomy as a foundation for sustainable economic development. Through sustained innovation, strategic investment, and supportive policy frameworks, bioeconomy strategies can fulfill their transformative potential in global decarbonization efforts while delivering multiple co-benefits for environmental sustainability and economic development.

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Part II
Technologies for a Circular Bioeconomy

Chapter 12
Diversifying Agriculture, Protecting the Environment, and Stabilizing Economies through Insect Agriculture

Jeffery K. Tomberlin, Kristin R. Duffield, Chelsea Miranda, Charity Owings, and Tong Wang

12.1 Introduction

Overview of Food Loss Waste of resources is a pervasive global issue with profound environmental, economic, and social implications. Unfortunately, this is not a new concern. In October 2015, the Food and Agriculture Organization (FAO) of the United Nations (UN) brought attention to the mounting global food loss and waste problem and its associated negative environmental, economic, and societal impact under its Sustainable Development Goal (SDG) 12 of Agenda 2030 (UN, 2015). Specifically, SDG Target 12.3 aims to "halve the per capita global food waste at the retail and consumer level and reduce food losses along production and supply chains including post-harvest losses" by 2030. In response, countries across the globe have committed to meet similar targets. In the United States (US), the US

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Department of Agriculture (USDA) and the Environmental Protection Agency (EPA) launched the U.S. Food Waste Challenge in June 2013 to reduce, recover, and recycle food waste by 2030. More recently in 2024, the US released its unprecedented *National Strategy for Reducing Food Loss and Waste and Recycling Organics* (The White House, 2024) to accelerate progress in this area. As 2030 draws nearer, more novel, innovative, and timely solutions are required to accomplish this ambitious goal of halving the amount of food waste currently being generated.

Food loss and waste remain an unbridled issue in many regions, and as the global human population continues to grow, the need to manage food loss and waste becomes more pressing. The sheer complexity of the issue partially explains the lack of a sustainable solution to food loss and waste. Adding to this complexity is the difficulty in simply defining food loss and waste (Garske et al., 2020). As distinctions between food loss and food waste are based on stages along the supply chain, each stage can have multiple definitions, leading to confusion among consumers and producers. The US recently adopted (The White House, 2024) the definition for food loss and food waste as "food produced for human consumption that leaves the human food supply chain for any reason (and is not ultimately consumed by humans)," distinguishing **food loss** as occurring "between production up to, but not including, the retail sector," and **food waste** as occurring "at the retail, food service or household sectors" (FAO, 2019). Moreover, collecting enough data to accurately and consistently estimate food loss and waste across the food supply chain is logistically challenging, requiring coordinated efforts, information sharing, infrastructure, resources, and technologies across numerous and diverse sectors, including industry, nonprofits, and local and federal government organizations (Xue et al., 2017; Corrado et al., 2019).

Food is lost along the entire spectrum of the supply chain, from production to consumption, for a variety of reasons (Spang et al., 2019). These include but are not limited to: farming practices (e.g., overproduction of crops), severe weather patterns, disease or pest outbreaks, insufficient human capital, improper handling (e.g., spoilage and packaging defects), insufficient infrastructure, faulty technology (e.g., electrical outage), failure to meet aesthetic standards during the harvest and retail stages, and consumer preference, lifestyles, and behaviors (Gunders, 2017). In Global North nations such as the US, estimates suggest approximately 30–40% of the food supply is discarded annually (Buzby et al., 2014). In 2022 alone, over 80 million metric tonnes of food in the US (roughly 38% of all food produced) was not sold or eaten, and approximately 36% of it ultimately ended up in landfills (ReFED, 2023). In the European Union (EU), over 53 million metric tonnes of food is wasted every year, which equates to about 131 kg per person (Eurostat, 2023).

The environmental, economic, and social impacts of food waste are chief motivators for addressing food loss and waste. Globally, food waste is the third leading source of greenhouse gas (GHG) emissions (e.g., carbon dioxide, methane, and nitrous oxide) behind the total emissions produced by China and the US, respectively (FAO, 2013). In fact, decomposing food waste in the US alone produces similar GHG emissions to 42 coal-fired plants (i.e., 170 million tonnes of carbon dioxide excluding landfill emissions) (Jaglo et al., 2021). Furthermore, wasted food takes up

a tremendous amount of space (at least 560,000 km^2 in the US) and accounts for enough water (i.e., 22 trillion L) and energy (i.e., 664 billion kWh) to supply 50 million American homes for an entire year (Jaglo et al., 2021). Furthermore, the resources (e.g., land, water, fertilizer ingredients, fuel, labor, materials) required to produce food that is ultimately discarded are also wasted. Ultimately, wasted food translates to wasted money and wasted nutrients. Indeed, in 2022 alone, the annual market value of food loss and waste in the US was valued at over $470 billion, and these uneaten calories amount to over 145 billion meals (ReFED, 2023). Notably not all wasted food can be diverted for human consumption and, because we produce far more food than could be consumed, increasing the redistribution of food alone would not meet the target goals for waste reduction (Jaglo et al., 2021). These costs are simply too expensive to sustain our current trajectory and so it is necessary to rethink approaches for managing food loss and waste to create a more sustainable and secure food future and preserve our natural resources.

Besides food destined for human consumption, other wastes (e.g., plastics, manure) have tremendous environmental, economic, and societal impacts that, if left unimpeded, will severely worsen with a growing global population. As of 2015, up to 6.3 billion tonnes of plastic waste had been produced, with only half of that waste incinerated, discarded into landfills, or recycled (Geyer et al., 2017). This means that most of the leftover 3,150 tonnes is quite literally littered across our landscapes and oceans. In response, plastic waste has been identified as the more pressing environmental issue, second only to climate change (Rochman et al., 2013). Solutions for safe, non-toxic biodegradation are increasingly necessary as plastic production continues to rise, with current trends estimating that we will have roughly 12,000 tonnes in landfills or the natural environment by 2050 (Geyer et al., 2017). Additionally, a steadily increasing demand for livestock products, especially in Global South countries, leads to increases in animal production and inevitably produces an overabundance of manure. While manure can be a highly valuable resource as an organic/ecological fertilizer for crop production, excess amounts pose significant negative impacts on our health (e.g., the release of antibiotic-resistant genes and bacterial strains), our environment (e.g., degraded water quality during field run-off and ammonia air pollution), and our climate (e.g., GHG emissions, of which manure accounts for 10% of total direct emissions (O'Mara, 2011)). As with plastic waste, developing new solutions to safely neutralize or divert excess manure is of critical importance.

Tackling our waste problem will require collaborative efforts across many sectors, from lawmakers and businesses to consumers and innovators. Numerous novel methods and technologies have been and are currently being developed (e.g., aerobic digestion, biochar), and it is highly likely that there is no one silver bullet solution. Insect agriculture, or the raising and breeding of insects as livestock (i.e., minilivestock, microstock) is rapidly demonstrating the potential to significantly and safely reduce our wastes (e.g., food, agricultural, plastic, manure/fecal) while producing high-quality products and ingredients to be used in food, feed, fertilizer, fuel, and other valuable commodities. Insects offer a natural and viable pathway toward reducing waste destined for landfills, or the natural environment, and contribute to building resilient and sustainable economies for future generations (Fig. 12.1).

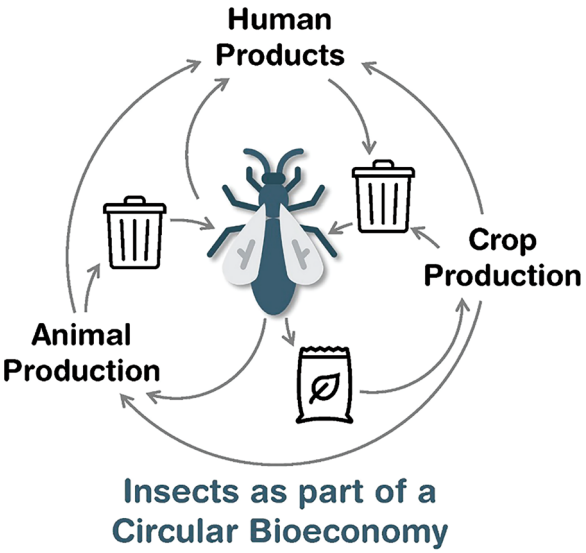

Fig. 12.1 Through their ability to convert no and low-value waste products (e.g., from animal production, crop production, and human waste), insects represent an integral component of a circular bioeconomy by producing valuable products (e.g., animal feed and human food ingredients, fertilizer, biofuel, etc.)

Insect Agriculture Overview Farming insects not only reduces the environmental impact associated with waste production but also addresses food security challenges by diversifying available protein sources for humans and animals. Even more, using insects to digest food waste is an attractive solution because insects can quickly convert food waste into multiple revenue streams beyond food and feed, including biofuels and biofertilizers. Equally, insects are full of useful compounds (e.g., antimicrobial peptides (Xia et al., 2021), anti-cancerous compounds (Moretta et al., 2020), chitin (Chavez et al., 2023)) that can be industrialized for pharmaceutical or cosmetic purposes. Additionally, insects can digest a variety of different food types, have quick generation times compared to other farmed animals, and can be implemented into existing agriculture systems to recycle a variety of pre- and post-consumer food waste.

The FAO estimates that cereal grains, fruits, and vegetables are among the most wasted food types across the globe with losses ranging from 38–50% (Gunders, 2017). From a nutritional standpoint, it should be no surprise that these foods have been extensively studied in waste reduction experiments involving insects. But this seemingly perfect pairing of wasted food and insects is not coincidental. The most widely produced insects for food and feed (crickets, Orthoptera: Gryllidae; black soldier flies, Diptera: Stratiomyidae; and mealworms, Coleoptera: Tenebrionidae) are typically reared on a standard diet consisting of grains, produce, and in some cases, animal by-products. However, even more impressive is that some insects, like the larvae of the black soldier fly, *Hermetia illucens* (L.), (Diptera: Stratiomyidae), have a voracious appetite for numerous types of organic wastes (e.g., food waste, animal renderings, manure). As insects represent the most diverse animal group on Earth, there may be many more currently unknown or understudied species with

instrumental benefits relevant to insect agriculture, food production, and waste management.

Another attractive feature of insect farming involves their rapid reproduction rates and short life cycles. New generations of insects can be produced in as little as a few weeks or months, translating into quick conversion of feed to insect biomass. Such characteristics could be advantageous for selective breeding for desired traits such as increased bioconversion rates and nutrient profiles. Further, a high reproductive rate makes them a highly efficient protein source with minimal environmental impact. Compared to traditional farming, insect farming uses less water and can employ vertical farming to reduce land usage. Insects are adaptable and can be reared in a variety of containers indoors or outdoors depending on the climate. The ability to use readily available materials makes it possible to establish and manage colonies with little startup funds. Still greater, the benefits to the environment and simplicity of the system have prompted investors to provide millions of dollars to the insect farming industry.

However, no matter the scale or how creative and impactful the idea may seem, it must be accepted by the target user (e.g., livestock, poultry, or aquaculture producer, and ultimately the consumer). While costs have decreased, feed cost in livestock production is significant. For example, in beef cow operations, feed accounts for 70% of the cost of production (Jones, 2000). Therefore, producers may be open to new technology that reduces their feed costs, especially if it is amenable for implementation into their current systems (e.g., consistent quality and texture in industrialized feeding operations). Along the same lines, diversifying agriculture with insects could reduce the growing competition for nutrients between humans (direct consumption) and livestock (indirect consumption) as the demand for crops that are also food for humans (e.g., soybean meal) would decrease. Intrinsically, insect farming provides a unique prospect to address multiple issues, such as waste management and the production of sustainable feed ingredients, while also increasing food security and freeing up land and natural resources needed to grow traditional animal feeds. Below, the use of insects in food, feed, and bioenergy production is discussed in more detail, along with current challenges in regulations, funding, research, acceptance, and safety.

Insect Species Used as Food and Feed Insect agriculture is an ancient practice, spanning many thousands of years. Evidence of the cultivation of cochineal insects for carminic acid used to make potent scarlet dyes dates back to the tenth century AD (Chávez-Moreno et al., 2009). Archeological data and genomic analyses revealed that the domestication of silkworms, *Bombyx mori* (L.) (Lepidoptera: Bombycidae) for silk production was likely initiated around 7,500 years ago (Yang et al., 2014). Neolithic (seventh millennium calendar BC) pottery containing traces of beeswax tells that the first human farmers may have been beekeepers (Roffet-Salque et al., 2015). Furthermore, insects have been harvested and semi-cultivated from the wild as a direct food source worldwide for millennia (DeFoliart, 1999; Hunter, 2021).

Today, insect farming remains an important industry where they are bred for pet and exotic animal food, biological control agents, and increasingly as a feed source for fish, poultry, and livestock, as well as ingredients in human food (van Huis et al., 2013). Of these, those previously mentioned—crickets, black soldier fly larvae, and mealworms (also referred to as the "Big Three") (Fig. 12.2)—stand out as the top-farmed insects for a variety of logistical, economic, and historical reasons. Most insect farms started as small to mid-sized operations, primarily as feed for pet and zoo animals, fish bait, and backyard bird feed. In the past two decades, modern insect farms have undergone a dramatic shift toward livestock feed, human food, and waste decomposition (Shockley et al., 2018). With this shift came tremendous growth in scale of production following concerted efforts and funding toward advancements in optimizing rearing practices, breeding and selection regimes, industrial innovations, automation, and product development (Glasner, 2023). Now, insect farms have grown to massive scales (Dossey et al., 2016; Ortiz et al., 2016) with the largest of these farms able to produce upwards of 100,000 metric tonnes of insect protein each year (Rivero, 2023).

Notably, other insects besides the "Big Three" such as grasshoppers (e.g., Orthoptera: Pyrgomorphidae in Mexico), wax moths (Lepidoptera: Pyralidae), cockroaches (Blattodea: Blattidae), palm weevils (Coleoptera: Curculionidae), and house flies (Diptera: Muscidae) are commonly farmed for various uses. The search to identify and select species for commercial uses is ongoing (Rumpold & Schlüter, 2013), and the potential for insects to diversify agriculture, protect the environment, and stabilize economies is not limited to the "Big Three." For example, Davidowitz (2021) proposes a habitat-centric approach as an alternative to the current species-centric approach whereby the insect is only selected after the habitat and waste streams—preferably endemic to the location—have been identified and characterized. As further research and innovation develop in this field, we imagine an array of insect-based products and services where species selection with their associated

Fig. 12.2 The "Big Three" insect of modern insect agriculture mass-reared for food, feed, fertilizer, and other products and ingredients. Photo credits: Adobe Stock (mealworms and crickets) and Amy Dickerson

breeding and rearing practices and technologies is optimized for preferred characteristics for the intended use.

Still, the "Big Three" are undoubtedly the most established and mass-produced insects worldwide for food and feed. Importantly, the husbandry of each insect differs significantly as well as their nutritional composition (i.e., amino acid profiles, lipid content, and micronutrients) and downstream products and applications (Payne et al., 2016; Riekkinen et al., 2022; Morales-Ramos et al., 2024). Finally, while there is evidence that each can convert organic waste side streams into usable ingredients and products to create a circular economy (Gasco et al., 2020; Kee et al., 2023; Siddiqui et al., 2024), there are notable considerations and limitations for each species.

Crickets Orthopterans (the insect order containing locusts, grasshoppers, katydids, and crickets) are generally edible, and many species are eaten regularly by humans throughout Africa, South America, and Asia (Magara et al., 2021). Field crickets (family Gryllidae) especially have been farmed across warmer temperate regions in the US since the 1940s, with most being produced for exotic zoo, pet food, and fish bait. Throughout the world, the most farmed species of crickets include *Gryllodes sigillatus* (Walker), *Acheta domesticus* (Linnaeus), and *Gryllus bimaculatus* (De Geer) (Orthoptera: Gryllidae). Within the past decade or so, cricket production facilities specializing in human-grade food have emerged and most insect-based packaged food products are made using crickets. These are typically in the form of whole-roasted and seasoned crickets or as ingredients in energy bars, protein powders, novelty snacks, pastas, and baked goods. Crickets may be more marketable as food in Western cultures for various reasons, including their appealing flavor profile and minor perceived "ick" factor compared to fly larvae and mealworms.

Crickets are highly nutritious, containing high amounts of proteins (up to 71%) and fat (up to 24%), as well as other vitamins and minerals (Zafar et al., 2023). Importantly, crickets contain some nutrients considered to be the most deficient in humans, such as iron, zinc, calcium, potassium, magnesium, manganese, folic acid, pantothenic acid, riboflavin, and biotin (Ayieko et al., 2016; Kosečková et al., 2022). Moreover, crickets have been shown to provide other health benefits, including antioxidant and anti-inflammatory properties, as well as the promotion of beneficial gut microbiota (Stull et al., 2018; Pilco-Romero et al., 2023). Research into the fortification of traditional staple foods (e.g., rice) with powdered nutrient-dense insects (Tao & Li, 2018) provides an opportunity to deliver critical nutrition in a safe, sustainable, appealing, and culturally relevant way.

While the average level of automation and scale for cricket production is currently far less than that of black soldier fly larvae and mealworms, the cricket industry is following a similar path of mass production. For example, Aspire Food Group recently (2022) finished completing the world's largest cricket production facility in London (Ontario, Canada) to produce *A. domesticus* crickets using highly automated processes with a purported capacity to produce 12,000 tonnes of cricket per year, with an equal tonnage of frass produced (Watson, 2023). While requiring

different rearing conditions than flies and beetles, crickets are also amenable to large-scale production. A full cricket life cycle can be completed in 4–6 weeks (Patton, 1963) and adult female crickets can lay about 25–30 eggs per day until they are about 60-day old (Murtaugh & Denlinger, 1985). Additionally, because crickets do not require a complete molt to mature, juvenile crickets can be reared in the same container from hatchlings to adulthood, and they are highly adaptable to captive living. Unfortunately, cricket producers have been particularly hard hit by viral pathogens that can reduce yield and lead to colony collapse (de Miranda et al., 2021; Duffield et al., 2021). While some are considering why the cricket industry currently faces more incidents of disease than other species, it suggests that insect farming is vulnerable to outbreaks just as in other traditional agricultural commodities (i.e., due to crop and animal diseases) and requires research and development toward improving and maintaining insect health for maximizing productivity (Eilenberg et al., 2015, 2018; Maciel-Vergara & Ros, 2017; Maciel-Vergara et al., 2021).

Field crickets are natural omnivores and can be sustained on a variety of agricultural by-products such as wheat bran, rice bran, brewer's yeast, and corn distiller's dried grains with solubles (DDGS) (Morales-Ramos et al., 2020). Moreover, a recent study revealed that crickets can safely convert corn-based diets contaminated with fumonisin B_1, a harmful mycotoxin produced by naturally occurring fungi that infect cereal grains, into high-quality protein (Paulk et al., 2024). Crickets, and other insects, could provide opportunities to valorize mycotoxin contaminated agri-waste, which currently costs the US economy ~$1B USD annually (CAST, 2003). Notably, unlike black soldier flies, crickets are general omnivores and are not specialized decomposers, so their physiology likely constrains their ability to convert wastes as efficiently. Still, the highly favorable nutritional profile and product marketability, coupled with the ability to convert important agricultural wastes, make crickets an insect of high interest as a food and feed resource.

Mealworms Likely native to Europe, the yellow mealworm (*Tenebrio molitor* Linnaeus) is now found worldwide. Despite their notorious reputation as a pest of stored grain, mealworms have been raised at a commercial scale and used as feeder insects for pet and zoo animals and fish bait for decades. While other species are farmed (e.g., lesser mealworms *Alphitobius diaperinus* (Panzer) (Coleoptera: Tenebrionidae) and superworms *Zophobas morio* (Fabricius) (Coleoptera: Tenebrionidae)), *T. molitor* is increasingly mass-produced and its larvae used for food and feed purposes. As with black soldier fly larvae, the realized scale of production for mealworms is massive. For example, the French company Ÿnsect recently built their largest facility and the largest insect facility at the time in Amiens (France), measuring 45,000 m^2 and 36 m high with the capacity to produce more than 200,000 tonnes of mealworm product (Tyler, 2021). The mealworm life-cycle is amenable to large-scale production as they thrive in dense populations. A single female can lay between 250–500 eggs, which can hatch within four days, and their life cycle is relatively short-lasting 75–90 days in total (Ribeiro et al., 2018).

Mealworm larvae are a rich source of macro- and micronutrients as they are high in protein (44–69% dry weight) and fat (23–47% dry weight), including a high content of oleic, linoleic, and linolenic acids, and are a good source of minerals such as copper, iron, zinc, magnesium, and potassium (Grau et al., 2017; Costa et al., 2020). They are considered a suitable source of protein in monogastric (e.g., pigs and poultry) animal feed, typically performing as well or better than traditional protein sources (Hong et al., 2020; Selaledi et al., 2020). Additionally, mealworm larvae have been successfully included in the diets of fish and aquaculture species (Henry et al., 2015; Shafique et al., 2021). Mealworm larvae are also included in human food products; in fact, mealworms were the first insect species to receive a positive opinion from the European Food Safety Authority (EFSA) as novel food (EFSA Panel on Nutrition et al., 2021). Of some concern, *T. molitor* produces chemical defense toxins (Attygalle et al., 1991), such as benzoquinone compounds, that can cause health complications, so future research is needed to determine toxin accumulation with insect age and processing methods. Additionally, studies have demonstrated that mealworms can sequester heavy metals (e.g., lead and chromium) from the waste products they consume (Noyens et al., 2023) and controlling accumulation is an active field of research (Cardoso et al., 2023) and will be essential for large-scale application of biotransformation of waste to food and feed ingredients. As with black soldier fly larvae, mealworm larval products go beyond food and feed, and applications have been used to produce biodiesel (Zheng et al., 2013), chitin and chitosan (Song et al., 2018), bioactive compounds (Errico et al., 2022), and biochar (Yang et al., 2019).

While their traditional commercial diet is comprised of cereal bran or flour supplemented with additional protein, there is increasing evidence that mealworms can be utilized for waste transformation (Van Broekhoven et al., 2015; Morales-Ramos et al., 2020). Incredibly, mealworms can also feed on inorganic wastes such as plastics, including polystyrene (Yang et al., 2015; Brandon et al., 2018). This could provide a scalable solution for environmental and waste management systems to address our growing global problem of plastic waste. Efforts by Pham et al. (2023) determined that 100 mealworms can consume (i.e., recycle) polystyrene and polypropylene at a rate of 7 mg and 4 mg per day, respectively, depending on the type.

Black Soldier Fly The black soldier fly is native to the Americas and is currently found worldwide in tropical and warmer temperate climates. In nature, the larvae of these insects thrive in dense populations on a wide variety of organic waste streams, including manure and rotting organic matter. Their status as saprophages (i.e., specialized to feed on dead and decaying matter) makes them ideally suited for waste biodegradation in commercial settings (Gold et al., 2018; Surendra et al., 2020). In fact, black soldier fly larvae can convert up to 78% of organic municipal waste into insect biomass (Diener et al., 2011). Because black soldier fly larvae can effectively reduce mass, moisture, offensive odors (Beskin et al., 2018), harmful pathogens (Liu et al., 2008; Lalander et al., 2015), pollutants, and even nuisance pests from organic waste and residue streams (Newton et al., 2005), they are currently used commercially for waste reduction in many countries. Importantly, black soldier fly

adults are not known to serve as vectors for human or animal pathogens and are no longer considered pests, which are integral traits when considering the ecological and environmental impacts of insect agriculture.

The size and production of black soldier fly farming operations is massive and, on average, the largest of the "Big Three." This colossal scale is due in part to the black soldier fly life cycle, which is highly conducive to rapid and large-scale production (Sheppard et al., 2002). The larvae thrive in dense populations and have a relatively short life cycle, with eggs hatching within 2–4 days and the larvae pupating in 14 days, and each female can lay up to 1,000 eggs throughout her lifetime. Furthermore, rigorous research efforts directed toward improving automation and increasing the scale of their production have significantly increased yield and reduced associated labor costs. As such, the black soldier fly is increasingly utilized for commercialized biotransformation whereby high volumes of no or low-value waste products are upcycled into safe and valuable applications such as in animal and pet feed ingredients, and other commodities (e.g., biodiesel, biopolymers, enzymes, and chitin as previously mentioned). Moreover, as with other insects, the by-products generated from insect production in the form of exoskeletons and feces (i.e., frass) are a highly valuable resource and used as a soil amendment in crop production (Gärttling et al., 2020; Beesigamukama et al., 2022).

There is mounting evidence demonstrating the ability of black soldier fly larvae to be safely incorporated into animal feed diets (Barragan-Fonseca et al., 2017), replacing or amending more traditional sources of protein in the diets of fish (Henry et al., 2015; Mohan et al., 2022), poultry (Abd El-Hack et al., 2020), and swine (Hong & Kim, 2022). As a source of nutrition, black soldier fly contains high levels of protein (35–57% dry weight) and fats (35% dry weight) (Lu et al., 2022) with very high levels of lauric acid (16–70% of total fat content), the latter of which has many applications such as in soaps and cosmetics due to its antibacterial and anti-inflammatory properties. While black soldier flies accumulate beneficial minerals (e.g., calcium and magnesium) from waste, toxic heavy metals (e.g., barium and mercury) can also bioaccumulate in black soldier fly larvae, posing a challenge to food and feed safety (Diener et al., 2015). However, processing larvae could eliminate these concerns by separating the valued commodities from the contaminants. In the end, such processes may allow for the black soldier fly industry to expand to terraforming or bioremediation of contaminated locations and allow future use of lands historically unavailable to humanity (e.g., Mars). For example, the removal of heavy metals from soil can be accomplished by growing plants on contaminated soils and then feeding the plants to insects where the metals are bioaccumulated (i.e., concentrated). Downstream processing can remove the heavy metals from the insects while generating protein and fats for other uses. Eventually, through numerous growth cycles, the soil contamination can be removed. To illustrate the role insects can play in supporting a circular agricultural bioeconomy, we will use the black soldier fly as an example, discussing their opportunities, challenges, and considerations in greater detail.

12.2 An In-Depth Review of the Black Soldier Fly

Animal Feed Black soldier fly larvae exhibit a broad diet comprising numerous biowastes (Nguyen et al., 2015; Parra Paz et al., 2015; Manurung et al., 2016; Miranda et al., 2020) with an efficient conversion rate of feed to biomass (Diener et al., 2009; Lalander et al., 2015; Parodi et al., 2020), leading to a significantly reduced carbon footprint compared to animals reared for meat (Nguyen et al., 2015; Tomberlin & Van Huis, 2020). Currently, this fly is approved in the US, EU, and other parts of the world to convert select wastes to insect biomass that can be used as feed for livestock, poultry, aquaculture, and even pets (AAFCO, 2016; Alagappan et al., 2022). Mass production and farming of black soldier fly larvae for animal consumption has been reviewed extensively in the last decade (Barragan-Fonseca et al., 2017; Wang & Shelomi, 2017; Abd El-Hack et al., 2020; English et al., 2021; Nairuti et al., 2021; Edea et al., 2022; Lu et al., 2022; Mohan et al., 2022), with many investigations demonstrating black soldier fly larvae as a promising alternative to traditional feed and feed ingredients. Many of these studies have shown comparable results (i.e., no negative impacts of black soldier fly feed and ingredients on animal health traits) to traditional feed and, in some cases, improved health, and performance of dairy cows (Nekrasov et al., 2022; Kahraman et al., 2023), beef steers (Fukuda et al., 2022), swine (Crosbie et al., 2021), sheep (Rahman et al., 2021), and horses (Burron et al., 2024) depending on the percentage of inclusion of black soldier fly larval fats and proteins in the formulation. Black soldier fly larvae are often used as a complement to corn and soy in poultry feed, improve carcass traits and meat quality in broiler chickens (Schiavone et al., 2017a, 2017b, 2018), improve nutritional, microbial, and physical characteristics of layer eggs (Kawasaki et al., 2019; Patterson et al., 2021), and provide an inexpensive and accessible nutritional resource for small farms (Nyakeri et al., 2017). One of the biggest areas employing the use of black soldier fly larvae as a protein and fat replacement is the aquaculture industry, where it has been successfully used as a suitable fishmeal replacement for several farmed fish species (Magalhães et al., 2017; Xiao et al., 2018; Zhou et al., 2018; Belghit et al., 2019; Oteri et al., 2021). The pet food industry has also begun including black soldier fly larvae in some dog and cat diet formulations, specifically to increase the sustainability of protein ingredients (Freel et al., 2021), demonstrating comparable (Kröger et al., 2020; Abd El-Wahab et al., 2021; Penazzi et al., 2021; Pezzali & Shoveller, 2021; Do et al., 2022) or improved palatability, digestibility, and immune response to traditional diet formulations (Lei et al., 2019).

Human Consumption Despite the growing enthusiasm for the integration of black soldier fly larvae into livestock, poultry, aquaculture, and pet foods either as whole larvae or as fractionated ingredients, as well as the overwhelming empirical support for the high nutritional value and low environmental impact of farming, a reluctance to partake in entomophagy among Western nations likely poses the greatest challenge toward acceptance of black soldier fly larvae for human consumption (Bessa

et al., 2020). However, westerners may be more willing to try insect-based foods if they are disguised in food ingredients such as flour, meals, and powders (Higa et al., 2021). Aside from societal barriers, the fact that black soldier fly larvae are a primary decomposer of microbe-laden resources makes this insect worthy of more thorough examinations in terms of safety for human consumption. As previously mentioned, black soldier fly larvae can suppress pathogens (Erickson et al., 2004; Lalander et al., 2015; Awasthi et al., 2020), antimicrobial-resistant bacteria (Liu et al., 2008) and antimicrobial-resistant bacterial gene frequencies (Cai et al., 2018a), degrade antibiotics (Cai et al., 2018b; Luo et al., 2022), and reduce some heavy metals in wastes (Wu et al., 2020; Bohm et al., 2022). Still, further investigations examining toxin sequestration in the end product, as well as proper disinfection and processing (Klunder et al., 2012), must be performed before black soldier fly larvae are considered safe for human consumption. At the very least, empirical examinations that support the safety of black soldier fly larvae and potential risks associated with contamination and allergenicity should be prioritized to have meaningful impacts on future legislation regarding human consumption of black soldier fly larvae.

Black Soldier Fly Use in Bioenergy Insects, particularly black soldier fly larvae, have been touted as an effective tool to address the challenges of environmental sustainability, renewable energy, and biobased agricultural products, ultimately achieving a more circular bioeconomy (Bosch et al., 2019; Chen et al., 2019; Pang et al., 2020a, 2020b; Magee et al., 2021). This is due to its extraordinary ability to transform wastes into high-value and high-quality biomass that is protein and lipid-rich (~44% and 35%, respectively, depending on diet and life stage). The high bioconversion performance of black soldier fly larvae (e.g., 1.4 kg feed transforms to 1 kg of black soldier fly larvae, less than the 2.3 and 3.8 kg feed required to achieve 1 kg of crickets or mealworms, respectively (Oonincx et al., 2015)), along with its minimum requirement for land and water, leads to significant reductions of greenhouse gas emissions (Pang et al., 2020a; Ebeneezar et al., 2021; Kristiansen et al., 2021). The insect farming industry is expected to continue rapid diversification in the EU and the US. Some have speculated the global black soldier fly market to reach $2.57 billion by 2030 (Doepel, 2020), or $3.96 billion by 2033 with 7.5 million tonnes of black soldier fly larvae (Meticulous Market Research, 2024); however, these numbers remain unconfirmed. This total volume of black soldier fly larvae is equivalent to 0.7 million tonnes (~787 million liters) of lipid available for biofuel conversion. This growth is mainly attributed to increasing demand for protein meal from animal feed manufacturers, rising soy meal prices, growing aquaculture industry, government support, and approval for insects to be used in animal feed and pet food, and growing investment by the key players of the industry.

Production of first-generation biodiesel (i.e., fatty acid methyl esters) and second-generation green diesel (having similar chemical composition and structure as petroleum diesel) from black soldier fly larval lipids has been reported

and reviewed (Franco et al., 2021; Suryati et al., 2023; Lee et al., 2024). For example, by transesterification, biodiesel of 86.5% yield was obtained (partially due to protein co-extraction), and all the parameters of biodiesel satisfied the Korea fuel standard (KS M 2965) except for oxidation stability (Park et al., 2022). To produce green diesel, black soldier fly lipids can be hydrodeoxygenated (i.e., the oxygen atom is removed in the presence of hydrogen), leading to better fluidity at low temperature compared to fuel converted from vegetable oil due to the carbon chain length distribution (Lee et al., 2024). This is one of the first studies validating black soldier fly larval fuel's desirable hydrocarbon chain length profile.

A novel application of black solider fly larvae is the use of its lipids for Sustainable Aviation Fuel (SAF) production using the approved Hydroprocessed Esters & Fatty Acids-Synthetic Paraffinic Kerosene (HEFA-SPK) pathway (ASTM D7566 Annex A2, 2011). The U.S. government aims to boost domestic SAF production to 11.3 billion liters (3 billion gallons) by 2030 and 132 billion liters (35 billion gallons) by 2050 through its landmark "SAF Grand Challenge" initiative. However, the current production capacity is estimated at 59.7 million liters (15.8 million gallons) per year (Krause, 2023), far below the SAF Grand Challenge's nearest target. While the exact figures are unknown, of the 59.7 million liters, SAF has thus far been predominantly produced through HEFA from oilseed lipids and waste (e.g., used cooking oil and tall oil). However, agricultural oilseed lipid feeds for HEFA SAF production are less economical compared to petroleum-derived jet fuel because of the expensive starting materials. If the lipid is recovered from non-food black soldier fly larvae that are grown on waste, the cost of producing SAF could be reduced when industrialized waste-to-insect conversion is established. Due to its higher degree of saturation and fatty acid chain length profile (relative richness in lauric acid, C12:0, Table 12.1), the black soldier fly larval lipid is more desirable for the conversion to short-chain fuel, which may potentially play a significant role in addressing the SAF Grant Challenge.

There are a few companies already engaged in the commercialization of black soldier fly larval oil-based fuel technologies. The Israeli startup BugEra and its researchers are building an insect genetics platform to develop new strains of the black soldier fly that could convert organic manure into biofuel. This will lead to an oil feedstock that can be highly suitable for the biofuel industry, including biodiesel, renewable diesel, and SAF. The FLEXI-GREEN FUELS project is an EU-funded research group with the goal of advancing the production of next-generation aviation and shipping biofuels. Production of alternative biofuel from black soldier fly larval oil by upgrading them through hydrodeoxygenation and isomerization has shown to be a viable alternative to aviation or shipping fuel. Key data, such as heating value, flash point, and freezing point, have been used to evaluate the performance of the hydrotreatment processes. These data have shown a high degree of deoxygenation and subsequential isomerization has reduced the number of unwanted compound classes.

Table 12.1 Fatty acid composition (%) of black soldier fly larvae and adults[a]

	Larvae	Adults
10:0	0.97	0.45
12:0	39.85	32.81
14:0	9.62	7.06
16:0	14.28	7.01
18:0	2.60	1.98
Total saturated	67.91	50.46
16:1	2.70	2.48
18:1	9.18	10.66
18:2	9.82	12.55
20:1	0.92	1.21
Total unsaturated	24.47	27.56
Total methyl-branched	0.59	1.0.46
Total cyclopropane	0.71	0.45
Total fatty acid	93.68	79.93

[a]Leyva-Gutiérrez et al. (2022)

12.3 Challenges

Regulations Organized and strategic advancements across multiple fronts are key to the expansion and stabilization of the insects as food and feed industry, which will act to secure its position as a reliable contributor to the global circular bioeconomy. The continued evolution of regulations within key regions of the world (e.g., the US and EU) to allow for mass rearing of insects on alternate organic side streams will be crucial for accomplishing such a goal. Current regulations limit the black soldier fly industry as other insects are produced on feed-grade materials that are already mass-produced (e.g., maize, soy, etc.). For example, the insect agriculture industry in Western nations (e.g., the US) is currently restricted to using preconsumer food waste for the mass production of the black soldier fly, restricting the growth of the industry in two key areas: (1) facility location and (2) waste material abundance and availability. In both cases, economics in part determine where facilities can be located as distance from these materials impacts costs. Furthermore, the amount of organic material available for digestion by the insect directly impacts the size of the facility being constructed. By allowing other resources to be used to mass produce the black soldier fly (e.g., livestock manure, post-consumer food waste), additional facilities can be constructed. Consequently, constructing additional facilities results in more jobs and products generated. These outcomes have downstream effects by providing resources for rural areas to bolster local economies while simultaneously protecting the local environment (e.g., reduced likelihood of water, air, or land pollution). Furthermore, creating more products (e.g., insect biomass) can allow the industry to meet the growing demand for pressured materials, including ingredients in animal food production.

Research and Funding Federal funding typically favors insect agriculture research that contains clear broader impacts. Though applied research is often narrowly focused (e.g., optimization for growth and bioconversion of black soldier fly larvae), there is the potential for major contributions in nanomaterials, textiles, sustainable packaging, and medical therapies using these insects. However, foundational research on many agriculturally important insects (including the "Big Three") is lacking, even though a basic biological understanding of these species would undoubtedly lead to progress in streamlining and optimizing large-scale insect husbandry for commercialization. Such understudied areas include behavioral (e.g., mating and courtship) and evolutionary (e.g., life history strategies) ecology, chemical ecology, digestive physiology, population genetics and genomics, host–pathogen–microbiome interactions, and basic ultrastructural morphology. For example, the wide knowledge gaps concerning the basic biology of all species within the "Big Three" hinder the progress that can and should be made with these species. The field would greatly improve through increased investment in biological and genetic resources for mass-reared species, like black solider flies, analogous to those in *Drosophila melanogaster* (the fruit fly, the insect model organism). As a model organism, black soldier flies could lead to additional unanticipated scientific discoveries, including those that will be critical in sustainable food production.

Safety In order to expand current regulations that limit the potential of insect agriculture, research is needed to demonstrate that the materials generated from such processes are safe. Materials that can potentially serve as feed substrates for insects include but are not limited to food loss, post-consumer food waste, contaminated agricultural products, plastics, and manure. However, each waste stream comes with its concerns, such as aflatoxin in agricultural products (e.g., maize and peanut), or *Salmonella* and *Escherichia coli* in manure. While data generated thus far are promising, efforts are still needed to demonstrate such outcomes are achievable at an industrial scale. Unfortunately, this body of work is sparse and fragmented due to limited funding opportunities available for such work, preventing widescale application. Federal funding agencies, including those in the United States, are encouraged to incorporate insect agriculture language within their funding opportunities to allow for data to be generated to fully realize the potential of insects as a component of the agricultural bioeconomy.

Educational Opportunities Though the insect agriculture industry has grown exponentially in the last decade, educational opportunities in this area are virtually non-existent. Currently, university-level degrees, concentrations, certificates, or even single courses on insect agriculture or insects as food and feed are almost entirely absent in the United States and most other countries. To our knowledge, the only current educational opportunities are limited to those in Europe (e.g., Summer School Insects as Food and Feed, Wageningen University, the Netherlands). Given the tremendous potential of this industry, it is critical that more opportunities open for both students and professionals to receive basic education and training in this area.

Public Acceptance of Insects as a Segment of the Bioeconomy Potentially the biggest barrier to the successful adoption of insects as food and feed is public perception, appreciation for diverse applications, and acceptance. Entomophagy, while only one piece of the bioeconomy puzzle, is what most might consider the key facet of this industry. Nonetheless, as demonstrated throughout this chapter, it represents one small component of the potential. Insects that are mass-produced can be used to recycle wastes, while also producing materials for various industries such as bioenergy, cosmetics, pharmaceutics, and even fertilizers. Consequently, a key challenge that remains is educating the public on the roles insects play within the bioeconomy and their value.

12.4 Conclusion

Insect agriculture can address food loss and waste and their associated economic and environmental impacts by upcycling the wastes to high-value biomass. It can diversify agriculture by providing alternative protein, lipids, and biomass as feed and potentially as foods and biofuel feedstock. The waste streams from the production and processing of insects can be used as biofertilizers. These insects, particularly crickets, black soldier fly larvae, and mealworms that are starting to be produced in an industrialized fashion, play a critical role in transforming agriculture, manufacturing, and socioeconomic structures that will lead to a global circular bioeconomy.

Insect farming and industry are now going through transformative changes from small, niche farms to large, automated facilities to produce insect-based products. Although there are great promises of insect farming, such as reducing wastes and landfills, neutralizing environmental toxins such as mycotoxins by crickets, removing harmful pathogens and pollutants by black soldier fly larvae, and plastic digestion and removal by mealworms, there are also challenges and limitations that need to be addressed. Further research and development, with financial support from multiple partners, can further drive the growth of the industry to optimize the production, processing, and diversity of product applications. Some of the examples of needs include:

- Foundational research characterizing, detecting, and preventing the diseases that reduce insect yield as well as research to improving insect health and resilience.
- Bioaccumulation of toxins and heavy metals from feed or diets and insect product safety concerns and validation.
- The presence of naturally produced toxins, such as benzoquinones in mealworm larvae, and possibly antinutritional factors in the insects.
- High-value and unique applications of insect-derived products beyond substitution for soybean and fishmeal for animal feed formulation.
- New insect species amenable to farming.

- Ultimately, insects will offer a natural and viable pathway toward reducing waste destined for landfills contributing to building resilient and sustainable economies for future generations.

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Chapter 13
Climate-Smart Technologies and Food Security in the Context of a Circular Bioeconomy: From Adaptation and Resilience to Mitigation

Gal Hochman, David Zilberman, Madhu Khanna, and Bruno Basso

13.1 Food Security

The concept of food security has evolved over the years, shaping the way policymakers address global hunger and malnutrition. Initially, food security was primarily defined in terms of providing enough calories for survival. Since the 1960s, the Food and Agriculture Organization (FAO) has used the "Prevalence of Undernourishment" metric to estimate the global number of hungry people by calculating total food consumption relative to the estimated levels of dietary energy requirements. The United States Department of Agriculture (USDA) later introduced the "Experience of Food Insecurity" scores, which were also adopted by the FAO. This measurement focuses on people's experiences of going hungry, skipping meals, or reducing food intake due to financial constraints (Masters & Finaret, 2024).

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Since the 1990s, the "Experience of Food Insecurity" metric has played a crucial role in assessing the number of people facing food insecurity. More recently, in 2021, organizations such as the FAO, International Fund for Agricultural Development (IFAD), and UNICEF have shifted their focus to measuring the affordability of healthy diets. By using retail prices of locally available foods to create the least-cost healthy diets that align with dietary guidelines in each country, this approach aims to distinguish among the various causes of malnutrition and guide targeted action to alleviate hunger and malnutrition. Overall, these innovative food security measurements offer hope in the global fight against food insecurity.

How should agencies and governments respond to food insecurity? When food prices are high, improving production and distribution methods is essential to make products more affordable for consumers. However, when individuals do not have sufficient funds to purchase nutritious food, they require increased income or support. If individuals can buy a healthy diet but opt for other food items, they should address the factors influencing their food choices. Nevertheless, between 702 and 828 million people worldwide faced hunger in 2021 (FAO et al., 2024).

To further understand the factors leading to hunger, it is crucial to understand the difference between "chronic" and "acute" food insecurity, as it can help us grasp the severity of food insecurity. Chronic food insecurity suggests persistent lack of access to an adequate food supply over an extended period, often due to systemic issues like poverty, inequality, and limited access to resources. This condition can result in malnutrition, hindered growth, and greater susceptibility to illness. Acute food insecurity is a short-term food insecurity, which can arise from sudden shocks like disasters, conflict, or economic crises and may result in hunger, malnutrition, and even famine. Structural factors such as poverty and inequality yield chronic food insecurity, while sudden shocks such as natural disasters and conflict lead to acute food insecurity. The impact also differs. Whereas chronic food insecurity yields malnutrition, stunted growth, and increased risk of diseases, acute food insecurity's impacts include hunger, malnutrition, and famine.

The issue of food insecurity is highly complex and necessitates a comprehensive approach. The root causes, such as poverty and inequality, must be tackled to address chronic food insecurity effectively. Additionally, governments and agencies should divert efforts toward resilience to sudden shocks that can lead to acute food shortages. It is important to highlight that providing emergency food assistance is not merely an additional measure but a critical intervention for individuals experiencing immediate need. By discerning between chronic and acute food insecurity, we can tailor our strategies more effectively and strive toward creating a world with enough food, which leads to a healthy and productive life, while minimizing food's environmental footprints. Strategies that build on biotechnology and bioinformatics can lead to crops that are more resilient to droughts and diseases and to technologies and practices that reduce the need for resources such as water and nitrogen.

The link between food insecurity and food deserts in both rural and urban areas often establishes a self-perpetuating cycle resembling a circular pattern. Food deserts are characterized by a lack of affordable and nutritious food options, which can result from factors such as distance to grocery stores, insufficient transportation, or

low-income levels (Ver Ploeg et al., 2009). Consequently, residents tend to depend on unhealthy alternatives available at convenience stores or fast-food outlets, leading to inadequate nutritional habits. These poor diets contribute to increased rates of obesity, diabetes, and various chronic illnesses. In turn, these health problems can lead to reduced productivity, higher absenteeism at work, and escalating healthcare costs, all of which intensify poverty and restrict access to vital resources (Hayes & Asres, 2022). Moreover, businesses may hesitate to invest in food deserts due to the belief that profits will be low, thereby sustaining the cycle of limited access to healthy food.

To tackle these challenges, it is essential to implement strategies that address the issue from various directions. Empowering local community members to initiate solutions such as community gardens, food cooperatives, and farmers' markets is important. Additionally, enhancing infrastructure, providing incentives for grocery businesses to establish themselves in underserved regions, and supporting local food systems are crucial. Raising awareness about nutrition, cooking methods, and advocating for healthy eating practices are also key. By comprehending the circular connection between food insecurity and food deserts, we can create more efficient and sustainable strategies to ensure that everyone has access to the nourishment they need to thrive.

Next, Sect. 13.2 covers agriculture, where we review solutions to food insecurity and the environment. The trade-offs introduced via current policy are discussed in Sect. 13.3, where we identify the trade-offs between the environment and agriculture. Section 13.4 introduces the CSCB framework, which plays a crucial role in evaluating the trade-offs between food insecurity, climate change, the environment, and biodiversity objectives. Section 13.5 argues that this approach presents a solution to these tensions, providing a comprehensive and sustainable strategy. In Sect. 13.6, we discuss ways economies can transition to the CSCB. We conclude with Sect. 13.7.

13.2 Unearthing the Hidden Cost of Food: Tackling Agricultural Waste and Pollution

Unfortunately, current agricultural practices negatively impact the environment. Agriculture, forestry, and land use (AFOLU) contribute to greenhouse gas emissions. The IPCC (2022) report states that AFOLU accounted for 13–21% of global anthropogenic greenhouse gas emissions between 2010 and 2019. These observations, while varying across studies, underscores the urgent need to address AFOLU's substantial impact on climate change. Reducing emissions from AFOLU is critical for mitigating climate change and achieving global climate goals. Strategies to reduce GHG emissions include sustainable land management practices, reducing deforestation, promoting sustainable agriculture, and exploring innovative solutions like carbon sequestration in soils.

The intensification of agriculture, driven by the need to produce more food for a growing global population, has led to increased use of inputs like irrigation water, fertilizers, and pesticides (Chartres & Noble, 2015). While these inputs are crucial for boosting yields, their overuse or improper management can have serious environmental consequences. For example, excessive irrigation can lead to waterlogging and salinization of soils, rendering them unproductive (Umali, 1993). More broadly, water footprint is significant and is influenced by crop type, climate, irrigation efficiency, agricultural practices, and livestock production, yielding challenging sustainability questions related to management, scarcity, and other factors (Mekonnen & Hoekstra, 2010; Hoekstra et al., 2012; Makarigakis & Jimenez-Cisneros, 2019). Other examples include fertilizer and pesticide runoff that contaminate surface and groundwater, harming aquatic ecosystems and potentially affecting drinking water sources (Agrawal et al., 2010). On the other hand, nutrient pollution can cause eutrophication in water bodies, leading to algal blooms, oxygen depletion, and fish kills (Bashir et al., 2020). Overuse of fertilizers can disrupt the soil's natural nutrient balance, leading to nutrient depletion and reduced soil fertility (Pahalvi et al., 2021). Heavy machinery used in intensive agriculture can contribute to soil compaction, reducing its ability to hold water and support plant growth (Hamza & Anderson, 2005). Intensive agriculture often involves monoculture cropping systems, reducing biodiversity and making ecosystems more vulnerable to pests and diseases (Gaba et al., 2015). Using herbicides can harm beneficial insects and pollinators, impacting the ecological balance (Nicholls & Altieri, 2013). Intensive agriculture contributes to greenhouse gas emissions through various processes, such as methane emissions from livestock and rice cultivation, nitrous oxide emissions from fertilizer use, and carbon dioxide emissions from deforestation and land-use changes.

Sustainable agricultural practices are crucial for mitigating intensification's negative environmental impacts. These practices include precision agriculture (Gebbers & Adamchuk, 2010), using technology to optimize input application, reducing waste, and minimizing ecological contamination. Other practices include integrated pest management (Barzman et al., 2015), which reduces reliance on chemical pesticides through biological, cultural, and mechanical control methods. Conservation tillage is another example of minimizing soil disturbance to preserve soil health and reduce erosion. Cover crops: Planting crops during the off-season protects the soil from erosion, improves water retention, and enhances nutrient cycling. Non-food intermediate oilseed crops like pennycress, carinate, and camelina can also be interseeded between primary crops so that vegetable oil can be used to produce biofuels. Crop rotation (i.e., alternating crops to improve soil fertility) reduces pest and disease pressure and breaks weed cycles. Some proposed practices to reduce agricultural water footprint include improving irrigation efficiency, adopting drought-tolerant crops, and implementing sustainable farm and livestock production practices. Finally, agroforestry integrates trees and shrubs with crops. These practices provide multiple benefits, such as soil conservation, biodiversity enhancement, and carbon sequestration. By adopting sustainable agricultural practices, we

can ensure that agricultural intensification meets the demands of a growing population while minimizing its environmental footprint.

Agriculture environmental footprint does not stop at the farm gate. Agricultural processing firms, such as those involved in meatpacking, dairy processing, and fruit and vegetable canning, can generate significant amounts of wastewater containing various pollutants, including nutrients. The sources of nutrients in wastewater from agricultural processing include waste products from processing, such as animal manure, blood, fat, and plant residues, which are rich in organic matter. When these materials decompose, they release nutrients like nitrogen and phosphorus into the wastewater. Cleaning processes in agricultural processing facilities use water and detergents, which can also contribute to nutrient loads in wastewater. Accidental spills and losses of products during processing can further increase the nutrient content of wastewater. The nutrient release yields eutrophication and excessive nutrients in water bodies, which can lead to eutrophication, algal blooms, oxygen depletion, and harm to aquatic life. High nutrient levels can impair water quality, making it unsuitable for drinking, recreation, and other uses. Contaminated water can harm human health by spreading waterborne diseases.

These outcomes lead regulatory agencies to set discharge limits for nutrients in wastewater to protect the environment and public health. Agricultural processing firms must comply with these regulations to ensure responsible wastewater management. To mitigate the environmental impacts, agricultural processing firms must implement effective wastewater treatment technologies to minimize the release of nutrients into the environment. Firms can remove solids and debris through screening and sedimentation, and one can use microorganisms to break down organic matter and remove nutrients like nitrogen and phosphorus (e.g., algae used to produce value-adding co-products). Employing additional processes like filtration, disinfection, and nutrient removal to further improve wastewater quality and treating and reusing wastewater within the facility to reduce freshwater consumption and minimize discharge can further alleviate the ramifications of the nutrient discharge.

The intensification of agriculture, coupled with the activities of agricultural processing firms, poses a significant challenge to environmental sustainability. It is crucial to adopt sustainable practices and innovative circular technologies to minimize the environmental footprint of these sectors and safeguard our natural resources. The adoption of circular practices is especially pertinent when discussing waste.

A proportion of agricultural biomass produced on the farm is wasted and not consumable as food. Of the consumable portion, losses before harvest, post-harvest, and during human consumption add to organic waste. Not all agricultural biomass produced is suitable for human consumption. Some crops may be damaged by pests, diseases, or adverse weather conditions, rendering them inedible. Even before crops are harvested, farmers may lose a portion due to natural shedding, mechanical damage during harvesting, or premature spoilage. After harvest, crops may be lost during storage, transportation, or processing due to improper handling, inadequate facilities, or contamination. Even the food that reaches consumers can contribute to organic waste. Plate waste, food spoilage at home, and expiration dates all

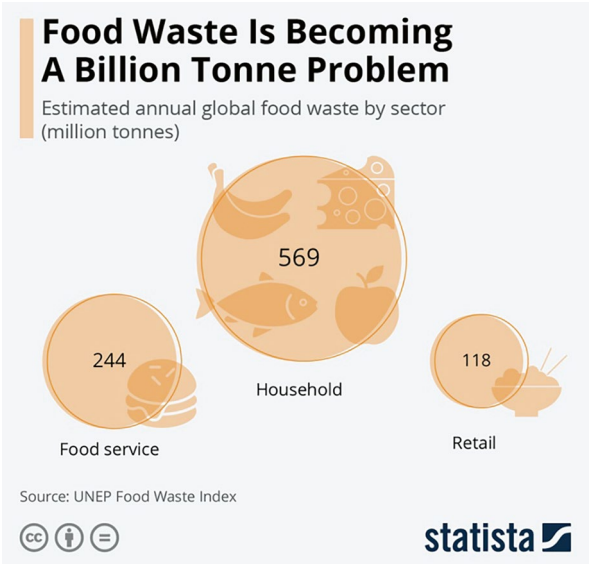

Fig. 13.1 Food waste volume, globally

contribute to this problem. The implied accumulation of organic waste has several negative environmental consequences, including decomposing organic waste in landfills, which releases methane, a potent greenhouse gas. On the other hand, leachate from decomposing organic waste can contaminate water sources. Finally, when organic matter is not returned to the soil, it can lead to nutrient depletion and reduced soil fertility. To reduce the organic waste in agriculture, we need to introduce a multifaceted approach. We need to improve farming practices and techniques like precision agriculture and integrated pest management, practices that help reduce crop losses in the field. One needs to invest in infrastructure and technology to minimize losses during storage, transportation, and processing. It is also vital to encourage consumers to plan meals, store food properly, and compost food scraps to reduce household waste (Fig. 13.1). Finally, circular strategies like diverting food waste from landfills through composting or anaerobic digestion generates valuable resources like compost and biogas. By addressing organic waste at every stage of the food system, we minimize its environmental impact and move toward a more sustainable agricultural model.

Managing agricultural wastes and residues poses a significant challenge for developed and developing economies. In many developing countries, these materials are frequently disposed of through burning or landfilling, leading to agricultural pollution. This type of pollution is a primary contributor to the degradation of surface and groundwater quality and the loss of soil health, hypoxic zones, and biodiversity. Circular agricultural practices are vital for the sustainability and resilience of agriculture supply chains.

13.3 Modeling the Trade-Offs between Environmental and Food Security Objectives

The world is currently grappling with numerous challenges, such as the expanding need for food, climate change management, and preservation of biodiversity. These challenges manifest as precipitation and temperature pattern alterations, escalating sea levels, desertification, invasion by non-native species, and the heightened intensity and frequency of natural disasters.

These surmounting challenges yielded various approaches, from digitalization and increasing input-use efficiency to using the bioeconomy to displace fossil fuels. Each approach, applied singly or in pairs, addresses some aspects of making agriculture more sustainable but may result in unintended consequences and trade-offs for other aspects. For example, the EU Green Strategy, a Climate-Smart strategy, emphasizes organic production practices and restricts the use of biotechnology in food production. This approach may lower the yield of crops compared to conventional practices and lead to a Malthusian trap, where we cannot meet the growing food demands of the global population (Mérel et al., 2023).

The Malthusian trap refers to a situation where population growth outpaces growth in food production. We have avoided a Malthusian trap by taking advantage of scientific knowledge and improving crop productivity, leading to the era of modern agriculture (Galor & Weil, 1999). The modern era has brought significant societal benefits, such as improved human health and economic well-being for a growing population. However, growth in the agricultural sector has also generated environmental externalities and contributed to climate change. Addressing these unintended outcomes is crucial to achieving sustainable development.

What happens if one does not utilize a system approach that integrates environmental and life science knowledge but focuses on only one objective? We show below, conceptually, that this may lead to a less efficient solution. This conclusion assumes uncertainty and limitations in obtaining reliable pollution-saving measurements, field-level soil health, and other parameters. To this end, stakeholders and the research community have raised a fundamental concern about the limitation of measuring, monitoring, reporting, and verifying many polluting aspects associated with the above challenges. Hence, uncertainty is inherent. While the seminal work of Weitzman (1974) showed how uncertainty might result in an advantage of using one instrument over another (Weitzman, 1974), we use this framework to derive conditions where the focus on one of several objectives is inferior to a multi-objective approach.

To illustrate the cost of one objective approach, assume the government focuses only on pollution and let y denote agriculture. Policy does not deal with food security; it only focuses on pollution. Furthermore, assume the government strives to reduce pollution by switching to fertilizer-free methods, thus bringing pollution to zero. Formally, assume an economy that produces good y using three inputs: land x_1 and pollution z associated with using fertilizers x_2. We capture uncertainty with two random and independently distributed variables θ and η.

We also assume the economy produces good y at a cost $C(y, \theta)$ that yields a benefit of $B(y, \eta)$—that is, there is uncertainty in production costs and revenues. Next, define the comparative advantage of ushering a multi-objective price policy yielding output y at $\tilde{y}(\theta)$ to that of a policy limiting pollution via fixing the output y at $\hat{y}$ (e.g., organic as opposed to conventional):

$$\Delta \equiv E\left[\left(B\left(\tilde{y}(\theta),\eta\right)-C\left(\tilde{y}(\theta),\theta\right)\right)-\left(B\left(\hat{y},\eta\right)-C\left(\hat{y},\theta\right)\right)\right] \tag{13.1}$$

The assumption of a multi-objective price policy is not key to the results, and other inclusive policies will yield similar or even stronger results (see below), favoring the deployment of multi-objective approaches.

We assume the amount of uncertainty is sufficiently small to justify a second-order approximation for the cost and revenue functions within the range of $\tilde{y}(\theta,\eta)$ around the neighborhood of $\tilde{y}(\theta,\eta)=\hat{y}$.

$$C\left(\tilde{y}(\theta,\eta),\theta\right)\cong C_0\left(\hat{y},\theta\right)+\left(\frac{\partial C}{\partial y}+\alpha_0\left(\theta\right)\right)\left(y-\hat{y}\right)+\frac{1}{2}\frac{\partial^2 C}{\partial y^2}\left(y-\hat{y}\right)^2$$

$$B\left(\tilde{y}(\theta,\eta),\eta\right)\cong B_0\left(\hat{y},\eta\right)+\left(\frac{\partial B}{\partial y}+\beta_0\left(\eta\right)\right)\left(y-\hat{y}\right)+\frac{1}{2}\frac{\partial^2 B}{\partial y^2}\left(y-\hat{y}\right)^2$$

where $C_0\left(\hat{y},\theta\right)$ and $\alpha_0(\theta)$ are stochastic functions and assume $E[\alpha_0(\theta)] = 0$, and similar for $B_0\left(\hat{y},\eta\right)$ and $\beta_0(\eta)$, respectively. These assumptions result in the following:

$$\Delta \cong \frac{\sigma^2\partial^2 B/\partial \mathrm{y}^2}{2\left(\partial^2 C/\partial y^2\right)^2}+\frac{\sigma^2}{2\partial^2 C/\partial y^2}$$

where σ^2 is the variance of $\alpha_0(\theta)$ (see Eq. (20) of Weitzman (1974)).

The value of Δ can be positive or negative, it depends on the magnitude of the two terms, an outcome to the inherent uncertainty surrounding the value chain. To this end, while focusing on a single market for agriculture, the $\frac{\partial^2 B}{\partial y^2}$ is the slope of the demand curve and $\partial^2 C/\partial y^2$ the slope of the supply curve. Staying with the demand and supply context, if the demand for good y is sufficiently elastic ($0 < -\frac{\sigma^2\partial^2 B/\partial y^2}{2\left(\partial^2 C/\partial y^2\right)^2} < \frac{\sigma^2}{2\partial^2 C/\partial y^2}$), $\Delta > 0$, and focusing on one objective is optimal. The rigidity surrounding amount purchase prevents too large deviations from the optimal amount of agriculture purchased—assuming we know the optimal amount. However, a multi-objective (price) policy yields a more favorable outcome if the supply curve is sufficiently inelastic, a characteristic inherent to agricultural production in the short run. This suggests many benefits from a holistic view that focuses on multi-objectives.

The conceptual analysis above points to the value of a holistic viewpoint that highlights the importance of pursuing various objectives. This viewpoint can be

pursued within the framework of a circular bioeconomy. This multifaceted strategy, which strongly emphasizes innovation and collaboration across sectors, is instrumental in building a resilient and sustainable circular production structure. The focus is on circular systems that effectively manage the various externalities associated with waste, pollution, and investments in research and development.

13.4 Climate-Smart Circular Bioeconomy (CSCB): Climate and Food Framework

For the reasons discussed above, we propose a framework that addresses the decarbonization challenge by combining climate-smart agriculture principles with circularity and a bioeconomy based on modern life science and information technology. This cross-disciplinary lens is crucial for policies that improve food security and its nutritional value and preserve one of the most critical assets of our planet, biodiversity. We refer to this multi-objective concept as CSCB, which includes climate-smart agriculture and forestry (O'Hara, 2024) practices but also introduces biotechnology and bioinformatics technologies while identifying biological-based solutions (Khanna et al., 2024). In addition to including agricultural and fossil fuel emissions within its framework, the CSCB embraces accumulating scientific knowledge and renewable resources to increase crop productivity and use of water and chemicals efficiently by increasing circularity, reducing waste, and resilience to increasing temperature and extreme weather events caused by climate change. There are many paths to a bioeconomy—some may be circular (reusing waste by-products), others may emphasize using new biomass sources, and a combination of both would be ideal. These paths may also vary in how climate-smart they are.

With a CSCB, agriculture production will produce more than food and fiber and contribute to making chemicals, pharmaceuticals, energy, and carbon sequestration from renewable natural resources. It expands the notion of the bioeconomy, a sustainable development strategy that utilizes modern life-, information and environmental sciences, and renewable resources to produce food, fuel, chemicals, and other commodities (Wesseler & Van Braun, 2017). The concept of a CSCB recognizes the importance of transitioning from non-renewable energy and chemical sources to renewable ones (CITE other chapters). It emphasizes using renewable resources in manufacturing and processing rather than just food, feed, and fiber production while building on life and information sciences advancements. Although wind and solar energy can help us make a substantial leap toward carbon neutrality, they have their limitations (Tong et al., 2021). The CSCB approach can use biomass and other living organisms to supplement solar and wind power by displacing fossil fuels and using land to store biological carbon and successfully transition the world economy to carbon neutrality (Pett-Ridge et al., 2023). Circularity should not come at any cost. By considering the social cost of untreated residues and waste and developing incentives to control them, residues will decline and be incorporated

into economically beneficial activities. With expanding knowledge in the life sciences and other disciplines, more reusing, reducing, and recycling technologies can be developed and enhance circularity over time (Fullerton et al., 2022).

Next, we discuss the foundations of CSCB (Sects. 13.4.1–13.4.3), where we view CSCB as encompassing many practices and technologies. Any specific practice or technology may not encompass all the components used to define it. A technology can be climate-smart (e.g., precision agriculture), or it may come from life sciences only (e.g., Bt cotton). However, other technologies may encompass all four elements discussed below. We view CSCB as a promising suite of technologies and practices that can adhere to the principles guiding climate-smart circular bioeconomy practices and technologies.

Next, we turn to climate-smart practices.

13.4.1 Climate-Smart Practices

Climate-smart practices are innovative solutions (Schultz et al., 2021) that aim to address the challenges of climate change (Liu et al., 2020). They do so by improving agricultural productivity, enhancing resource efficiency, and reducing greenhouse gas emissions (Liu et al., 2021).

13.4.1.1 Precision Agriculture

One such climate-smart practice is precision agriculture, an innovative and sustainable approach that utilizes advanced technology to enhance agricultural efficiency, productivity, and sustainability (GAO, 2024). This approach involves targeted application of fertilizers, pesticides, and water, thus minimizing overuse and runoff and reducing pollution of soil and waterways. By precisely applying these inputs only where needed, precision agriculture minimizes environmental impact and promotes conservation.

Precision agriculture plays a crucial role in supporting a climate-smart circular bioeconomy by optimizing resource use, reducing waste, and enhancing the efficiency of agricultural production. By providing precise and timely information on crop and livestock needs, precision agriculture enables farmers to make informed decisions about resource allocation, minimizing the use of inputs such as water, fertilizer, and pesticides. This not only reduces environmental impact but also improves economic efficiency.

One major advantage of precision agriculture is the reduced fuel consumption (Bora et al., 2012). This is achieved through optimized machinery routes and variable rate technology, which minimize fuel consumption and emissions, contributing to a more sustainable farming practice. These advancements also result in a reduction in production costs.

Furthermore, precision agriculture enhances resource efficiency through water conservation and fertilizer optimization (GAO, 2024). Soil moisture sensors and advanced irrigation systems ensure that water is delivered precisely where and when needed, reducing water wastage via reducing water withdrawals and alleviating pressure on surface or groundwater sources. Additionally, by varying fertilizer application rates based on soil nutrient levels, precision agriculture minimizes fertilizer overuse, saving costs and preventing nutrient runoff, thus improving resource efficiency.

In addition to reducing environmental impact and enhancing resource efficiency, precision agriculture also contributes to improving overall productivity (Balafoutis et al., 2017). This is achieved through yield optimization, where precision agriculture addresses crop needs at a granular level, thereby helping to maximize yield potential. Furthermore, remote sensing and data analytics enable early identification of crop stress or disease, allowing for timely intervention and minimizing losses.

Although precision agriculture offers tremendous potential for improving farm efficiency and sustainability, widespread adoption does face some key challenges. It involves high initial costs. The initial cost of precision agriculture technologies like sensors, GPS systems, drones, and software can be substantial, especially for smaller farms. In addition, some technologies require investments in farm infrastructure, like reliable Internet connectivity for data transfer and analysis. Another challenge is the need for data management and analysis. Precision agriculture generates massive amounts of data. Farmers need the tools and expertise to effectively manage, analyze, and interpret this data to make informed decisions. Lack of standardization across different technologies can make integrating and analyzing data from various sources difficult. The need for the complexity mentioned above demands expertise and, thus, training. Farmers and farmworkers need training to operate and utilize precision agriculture technologies effectively. Interpreting data and converting it into actionable insights requires a certain level of analytical skill. Many of these challenges are augmented further in rural communities, and farmers are concerned about who owns and controls the data generated by precision agriculture systems and how others might use it. Finally, it might be challenging to quantify the exact economic benefits of precision agriculture, making some farmers hesitant to invest.

Precision agriculture is a sustainable and forward-thinking approach that leverages technology to revolutionize farming practices. It boosts agricultural productivity and minimizes environmental impact, making it a crucial aspect of modern and sustainable agriculture. However, a few challenging barriers might prevent it from fulfilling its full potential and reaching the adoption rates some expect.

13.4.1.2 Agroforestry, Economic Viability, and Environmental Benefits

Another CSCB approach is agroforestry, a land-use management system that intentionally integrates trees and shrubs into agricultural landscapes (Ramachandran Nair et al., 2009). It combines agriculture and forestry to create more diverse, productive, profitable, healthy, and sustainable land-use systems.

Agroforestry integrates trees into agricultural landscapes, combining them with crops and livestock on the same land. This integration can be implemented in various forms, such as alley cropping (planting trees in rows with crops between). Alley cropping entails growing crops between rows of trees, providing windbreaks, and improving soil fertility. Other forms include silvopasture (combining trees with grazing livestock), where combining trees with grazing provides animal shade and protect crops and livestock from wind and high temperatures. Finally, riparian buffers involve establishing trees and shrubs along waterways to improve water quality and provide habitat, benefiting biodiversity (Coelho, 2017).

Trees, through photosynthesis, capture and store carbon dioxide from the atmosphere (Fig. 13.2). Agroforestry systems can significantly increase carbon sequestration in agricultural landscapes, helping mitigate climate change. In addition, tree roots help prevent soil erosion, improve water infiltration, and add organic matter to the soil, enhancing its structure and fertility.

Agroforestry systems create a more diverse habitat than monoculture agriculture, supporting a wider range of plants, animals, and insects. This increased biodiversity contributes to ecosystem health and resilience. Apart from carbon sequestration, agroforestry can also reduce greenhouse gas emissions by decreasing the need for synthetic fertilizers and pesticides. Trees can also provide shade and reduce wind

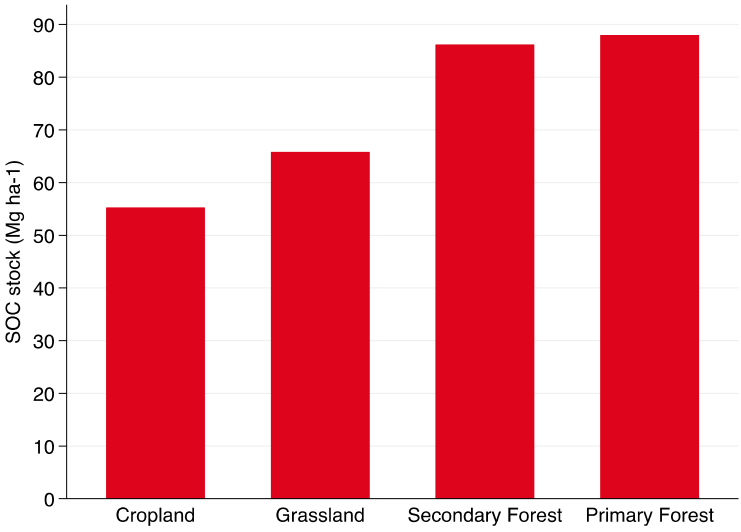

Fig. 13.2 The stock of soil organic carbon

and temperatures, leading to lower energy consumption for irrigation and crop protection. Agroforestry enhances water quality through natural processes that filter pollutants and reduce sedimentation, benefiting aquatic ecosystems and human communities.

Agroforestry systems can offer diversified income streams through timber, fruits, nuts, or other tree products. This can make farms more resilient to market fluctuations and climate risks. When it comes to the economy, the practice of diversifying income streams by incorporating timber, fruits, nuts, and other tree products provides both immediate financial gains and long-term improvements in the sustainability and resilience of farms. This diversification can increase the long-term productivity and resilience of farms, providing a sense of security about the future. Furthermore, integrating natural pest control and nutrient cycling can reduce input costs, contributing to the overall economic sustainability of farming operations.

However, several challenges and barriers hinder its widespread adoption. From a technical point of view, choosing the right tree and crop species for specific site conditions and desired outcomes requires careful planning and knowledge. In addition, agroforestry systems can be more complex to manage than monoculture systems, requiring knowledge of tree–crop interactions, pruning techniques, and pest and disease control. Trees and crops may compete for light, water, and nutrients. Careful management is needed to balance these needs. From an economic perspective, establishing agroforestry systems often requires upfront investment in tree seedlings, labor, and potentially land preparation. Trees take time to mature and provide economic benefits, which can be a barrier for farmers seeking immediate income or needing deep pockets. Many farmers lack awareness of the benefits and techniques of agroforestry. It is crucial that government policies adequately support agroforestry, providing incentives and technical assistance programs. To this end, more research is needed to develop and refine agroforestry practices for different contexts. Extension services need to disseminate this knowledge to farmers effectively. Land-use regulations may restrict tree planting in certain areas or require permits, creating barriers to agroforestry.

Agroforestry represents a sustainable and multifunctional approach to agriculture that offers numerous environmental and economic benefits. Agroforestry is a dynamic and adaptable approach that farmers can tailor to specific local conditions and objectives. By integrating trees and shrubs into agricultural systems, agroforestry offers a pathway toward more sustainable and resilient landscapes that benefit both people and the planet. However, existing challenges prevent it from expanding further.

13.4.1.3 Renewable Energy in Agriculture

Renewable energy is playing an increasingly important role in agriculture, offering a sustainable and cost-effective way to power farms and reduce their environmental impact.

Renewable energy offers numerous benefits for the agricultural sector. By harnessing renewable energy sources, farmers can significantly reduce their dependence on fossil fuels (FAO, 2011), reduce their electricity costs (IRENA, 2016), and contribute to reducing greenhouse gas emissions. This proactive approach helps combat climate change and improves air quality. Moreover, embracing renewable energy makes farmers more self-sufficient and less vulnerable to energy price fluctuations. In grid outages, renewable energy systems provide a complementary power source, ensuring uninterrupted farm operations (IRENA, 2022). Additionally, farmers can contribute excess renewable energy back to the grid, creating an additional income stream (O'Hara, 2024; Winikoff & Maguire, 2024). For example, Winikoff and Maguire (2024) show that the average annual payment to the operators, in 2020 US$, was more than $30,000.

Renewable energy sources come with their own set of challenges and considerations. First, there is the significant initial investment required for renewable energy systems, although costs have been decreasing lately (IRENA, 2022). Additionally, some renewable sources, such as solar and wind energy, are reliant on weather conditions and may necessitate energy storage solutions or backup power sources (NREL, 2019; Muthu & Dash, 2021). Moreover, the establishment of large solar or wind farms may take up substantial land areas, potentially encroaching on agricultural production. To this end, a recent report (Maguire et al., 2024) suggests although wind is compatible with agriculture land, while we do observe land-use competition between solar and agriculture.

Some examples of renewable energy in agriculture include

- Solar-powered irrigation pumps to reduce reliance on diesel fuel (Ishaq & Dincer, 2020)
- Wind turbines powering grain dryers and other farm equipment (Lamidi et al., 2019)
- Biomass-fueled heating systems for greenhouses and livestock barns (Kaltschmitt et al., 2002)
- Geothermal heat pumps providing efficient heating and cooling for farm buildings (Alberti et al., 2018)
- Hydropower systems generating electricity for remote farms (Rahman et al., 2022)
- Capturing methane that would otherwise be emitted from livestock manure or food waste and using this biogas/renewable natural gas (O'Hara et al., 2023) to produce electricity, be used as a transportation fuel, or substitute for fossil natural gas as industrial process heat.

Adopting renewable energy in agriculture offers economic and environmental benefits for farmers and the planet. As technologies advance and become more affordable, renewable energy is poised to play a more significant role in creating a more sustainable and resilient agricultural sector. Next, we discuss one such technology.

13.4.1.4 Agrophotovoltaic Systems

Agrophotovoltaic systems, also called agrivoltaics or dual-use solar, are an innovative approach to land management that combines solar energy production with agriculture on the same land (Weselek et al., 2019). This combination of solar and agriculture is achieved by installing solar panels above crops or grazing areas, creating a symbiotic relationship between energy generation and food production.

There are numerous benefits of agrophotovoltaic systems. These systems increase land-use efficiency by generating clean energy and producing food on the same land. Agrophotovoltaic systems also maximize land productivity and help reduce pressure on natural habitats. These systems also improve crop yields. The partial shade provided by solar panels reduces water evaporation, protects crops from extreme heat and weather events, and creates a more favorable microclimate for certain plants, potentially leading to increased yields. The shade from solar panels can decrease water needs for irrigation, conserving water resources, especially in arid regions. There is a symbiotic relation, as plants enhance solar panel's efficiency. The evapotranspiration from plants below the solar panels can help cool the panels, increasing their efficiency and energy output. Like agroforestry, agrophotovoltaic systems generate additional income for farmers. Farmers can benefit from selling the electricity generated by the solar panels, providing an extra source of revenue and making their operations more resilient. In addition, agrophotovoltaic systems can provide habitat for pollinators and other beneficial insects, supporting biodiversity and promoting ecological balance.

The challenges with agrophotovoltaic systems are their cost. Installing agrophotovoltaic systems can be more expensive than conventional ground-mounted solar installations due to the need for specialized structures and careful planning. It can also negatively impact yield, altering the microclimate below the installed system. Furthermore, not all crops are suitable for agrophotovoltaic systems, and farmers must adapt their agricultural practices to optimize yields under partial shade. The agrophotovoltaic systems also require careful design and maintenance to maximize solar energy production and agricultural productivity.

Overall, agrophotovoltaic systems offer a promising solution for sustainable land use, addressing the challenges of climate change, food security, and energy demand (Dohlman et al., 2023). By integrating renewable energy generation with agriculture, agrophotovoltaic systems have the potential to create a more resilient and productive supply chain.

13.4.2 Climate-Smart Bioeconomy Technologies

A climate-smart bioeconomy utilizes renewable biological resources and processes to create products and services that contribute to climate change mitigation, adaptation, and sustainable development.

These technologies involve the manipulation of crops and livestock (biotechnology) and the application of computational tools and analyses to biological data (bioinformatics).

13.4.2.1 Biotechnology

Biotechnology plays a crucial role in enabling climate-smart agriculture, helping farmers adapt to and mitigate the impacts of climate change while ensuring food security. Biotechnology yields the development of resilient crops. Biotechnology allows for developing crops resistant to drought, heat, flooding, pests, and diseases, all becoming more prevalent with climate change. This advancement increases yields and reduces losses even under stressful conditions. For example, biotech-developed maize and soybean varieties are already helping farmers cope with drought conditions. Bt crops reduce the need for pesticide applications, saving fuel and decreasing greenhouse gas emissions.

More broadly, biotech can help reduce greenhouse gas emissions from agriculture in several ways. Crops engineered to use nitrogen more efficiently reduce the need for synthetic fertilizers, which are a significant source of greenhouse gas emissions. Biotech traits that enable reduced tillage and cover crops promote carbon sequestration in soils, helping remove carbon dioxide from the atmosphere. Biotech can also be used to improve feed efficiency in livestock, reducing methane emissions, a potent greenhouse gas. Biotechnology can create crops that require less water, fertilizer, and pesticides, reducing environmental impacts and improving sustainability. In addition, biotech plays a crucial role in developing advanced biofuels from non-food crops or agricultural waste, providing a renewable alternative to fossil fuels. Companies use biotechnology to produce algae-based biofuels. Research is ongoing to develop algae as a sustainable source of biofuel that does not compete with food production. And finally, biotech-based innovations can extend the shelf life of produce, reducing food waste, which is a significant contributor to greenhouse gas emissions.

Other examples of the use of biotechnology to enhance the nutritional content of crops include biofortification. Biofortification can improve the nutritional value of crops, contribute to food security, and reduce the need for dietary supplements, which have environmental impacts. Another example is the microbe-based solutions. Biofertilizers and biostimulants enhance soil health and nutrient use efficiency, reducing fertilizer needs and promoting carbon sequestration.

However, challenges exist, the primary one being public acceptance. Concerns about genetically modified organisms (GMOs) and their potential environmental and health impacts persist in some regions. Concerns regarding GMOs lead to regulatory frameworks that become a stumbling block for the use of biotechnology. To this end, transparent and science-based regulations are needed to ensure biotechnology's safe and responsible use in agriculture. A concern that is more pertinent in developing countries is accessibility and affordability. There is a need for

biotechnology solutions to be accessible and affordable for farmers, particularly in developing countries.

Biotechnology has the potential to revolutionize agriculture and contribute significantly to climate-smart practices. Biotechnology can play a crucial role in feeding a growing population while protecting the planet by developing crops that are resilient to climate change, reducing greenhouse gas emissions, and promoting resource efficiency (USDA, 2024).

13.4.2.2 Bioinformatics

Bioinformatics, the application of computational tools and analyses to biological data, is crucial in enabling climate-smart agriculture. By leveraging the power of data and computation, bioinformatics can help address the challenges posed by climate change.

Bioinformatics can lead to crop improvement. Bioinformatics can analyze massive genomic datasets to identify genes associated with tolerance to drought, heat, salinity, and other climate-related stresses. This information can be used in breeding programs to develop climate-resilient crop varieties. Genomic selection and other bioinformatics tools can speed up the breeding process, allowing for faster development and deployment of climate-adapted crops.

Bioinformatics can also yield better resource management. Bioinformatics enables data analysis from sensors, drones, and satellites, allowing for precise application of water, fertilizers, and pesticides, reducing waste and minimizing environmental impacts. By analyzing weather data, soil conditions, and crop growth patterns, bioinformatics can help predict crop yields, identify potential risks, and optimize farm management practices.

Bioinformatics tools can analyze the genetic material of entire microbial communities, helping to understand the complex interactions between plants, microbes, and the environment. This knowledge can be used to promote soil health, nutrient cycling, and other ecosystem services crucial for climate-smart agriculture. By analyzing the genetic diversity of wild relatives and landraces, bioinformatics can identify valuable traits and genetic resources that can be used to enhance the resilience and adaptability of agricultural systems.

Bioinformatics can help in climate change mitigation. Bioinformatics can contribute to the development of sustainable bioenergy sources, such as algae-based biofuels or crops engineered for higher biomass production, helping to reduce reliance on fossil fuels. Bioinformatics models can help estimate the carbon sequestration potential of different agricultural practices and land management strategies, aiding climate change mitigation efforts.

There are, however, challenges science needs to overcome. Access to high-quality, diverse, and standardized agricultural and environmental data is crucial for effective bioinformatics applications. Analyzing large-scale biological datasets requires significant computational infrastructure and expertise. Effective

partnerships between researchers, farmers, policymakers, and other stakeholders are essential to translate bioinformatics insights into actionable climate-smart solutions.

In sum, bioinformatics is a powerful tool that can accelerate the development and adoption of climate-smart agricultural practices. By harnessing the potential of data and computation, bioinformatics can help create a more sustainable and resilient agricultural sector in the face of climate change.

13.4.2.3 Drought-Resistant Crops

Drought-resistant crops are another important topic. Developing and adopting genetically modified or conventionally bred crops that can thrive in water-scarce conditions helps mitigate the impact of climate change on agriculture (Ma & Rahut, 2024).

Climate change is expected to increase the frequency and severity of droughts in many regions. By relying less on irrigation, these crops can help conserve water resources, which are increasingly precious in many areas. Some drought-tolerant crops have deeper root systems or other traits that can improve soil structure and water retention, contributing to long-term soil health and resilience. By reducing the need for irrigation, which often relies on energy-intensive pumping systems, these crops can help lower greenhouse gas emissions from agriculture.

Whether genetically modified or conventionally bred, crops that require less water or tolerate drought conditions better are a testament to the potential of biotechnology in ensuring a stable food supply even in challenging conditions. While both can be instrumental in developing drought-resistant crops, using these technologies responsibly and with appropriate oversight is crucial. This ensures we maximize their benefits while minimizing any potential risks.

13.4.3 The Circular Bioeconomy

The discussion so far leads us to the circular bioeconomy (Mehta et al., 2021), a sustainable economic model that focuses on using renewable biological resources in a closed-loop system, minimizing waste and environmental impact. It aims to replace the traditional linear "take-make-dispose" model with a regenerative approach that promotes resource efficiency and reduces reliance on fossil fuels.

In the circular bioeconomy, renewable biological resources play a vital role, including crops, forests, algae, and organic waste. These resources are utilized cascadingly, ensuring maximum value is extracted from each resource before being recycled or composted. Furthermore, the circular bioeconomy emphasizes waste minimization by designing products and processes to minimize waste generation and maximize resource recovery. This approach not only reduces pollution but also contributes to a cleaner environment.

Renewable energy sources such as solar and wind power are integrated into bio-based production processes to reduce greenhouse gas emissions further. Additionally, the circular bioeconomy encompasses the entire life cycle of products and processes, from sourcing raw materials to end-of-life management. This holistic perspective ensures that environmental and social impacts are considered at every production and consumption cycle stage. To this end, Fig. XX depicts the life-cycle greenhouse gas emissions of SAF with and without the inclusion of climate-smart farming practices (Yoo et al., 2022; O'Hara et al. 2023; O'Hara, 2024). This work suggests that the introduction of CSA reduced corn emissions by about 10 gCO2/MJ, but only by about 5 gCO2/MJ for soybeans (Fig. 13.3).

The circular bioeconomy is a sustainable economic model that uses renewable resources, waste minimization, and efficient resource utilization to mitigate environmental impact, enhance resource security, drive economic growth and job creation, foster rural development, and address climate change (Schipfer et al., 2024). By diversifying raw material sources and promoting sustainable production practices, the circular bioeconomy reduces reliance on finite resources and improves overall resource security. This approach encourages innovation, opens new business opportunities, and contributes to economic growth and job creation across various sectors. Additionally, the circular bioeconomy can play a crucial role in rural development and revitalization by effectively utilizing agricultural and forestry resources. Moreover, by reducing greenhouse gas emissions, promoting carbon sequestration,

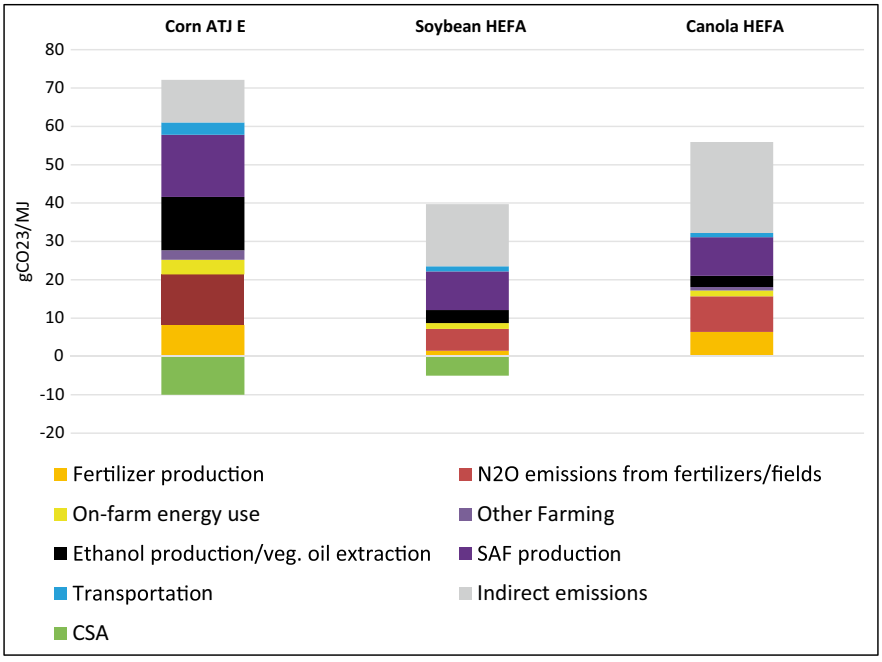

Fig. 13.3 The effect of climate-smart agriculture practices on emissions from agriculture

and enhancing agricultural practices, the circular bioeconomy helps mitigate climate change and build resilience to its impacts.

Furthermore, in a circular bioeconomy, organic waste from agricultural and food production processes is transformed into valuable products (Leong et al., 2021), such as bioenergy from crop residues, biogas from food waste, and bio-based materials from agricultural by-products through biorefinery processes. The circular bioeconomy also promotes closed-loop systems where the waste from one process becomes the input for another, thus minimizing resource depletion, reducing environmental impact, and improving overall system efficiency. Moreover, it encourages developing and using bio-based materials and products derived from renewable resources, such as bio-based packaging, biodegradable materials, and bio-based chemicals. These diverse factors are interconnected and contribute to the overall promotion and implementation of the circular bioeconomy concept across different countries, aiming to achieve sustainable development and environmental stewardship.

Circularity introduces a discrete change in production, with the current emphasize on valorization and a positive discrete jump to the value of production through an increase in profits and employment. Formally, denote the co-product production using lower-case letters, and define the co-product profits π_c as

$$\pi_c = b\left(h\left(y\left(\theta\right)\right),\eta_2\right) - c\left(h\left(y\left(\theta\right),\theta\right),\theta\right)$$

Then, assuming $\pi_c > 0$ that circularity introduces added value with the parameter η_2 denoting uncertainty associated with the co-product benefits. Circularity will increase the benefits from a multi-objective policy, i.e., the value of Δ (Eq. (13.1)) increases, and internalize the multiple objectives faced by the politician—the social benefit of R&D and the cost of pollution. That is,

$$E\Big[\left(B\left(\tilde{y}\left(\theta\right),\eta\right) - C\left(\tilde{y}\left(\theta\right),\theta\right)\right) + \left(b\left(h\left(y\left(\theta\right)\right),\eta_2\right) - c\left(h\left(y\left(\theta\right),\theta\right),\theta\right)\\ -\left(B\left(\hat{y},\eta\right) - C\left(\hat{y},\theta\right)\right)\Big]$$

is larger than Δ—the waste in one s, the outcome of introducing circularity.

Next, we examine how the various factors come together, how they are connected to different definitions, and how countries interpret them. We explore the synergies created through CSCB practices.

13.5 The CSCB Approach as a Climate and Food Initiative

Food security and environmental sustainability are inherently interconnected. Achieving one without the other is unsustainable in the long term. Therefore, integrating food security and environmental policies is critical to ensure a future where

everyone has access to safe and nutritious food while safeguarding the natural resources that underpin food production. Although themes of the CSCB have been introduced in the past through climate-smart practices and the reuse of (food) waste to produce energy and fuel, we emphasize that the solution needs to draw from the vast knowledge in life and information sciences. The emphasis on interdisciplinary work cannot be under-emphasized, and thus, the need for a multi-objective policy agenda that builds on circularity and the bioeconomy—namely, the CSCB approach is vital.

The CSCB concept involves understanding the intricate interconnections between different elements of food systems and the environment. It recognizes that decisions made in one aspect of the food system can have far-reaching impacts on other (environmental) areas. One should enhance agricultural productivity while minimizing adverse environmental effects, which involves adopting input-use efficiency practices, precision agriculture, and sustainable resource management to achieve efficient and sustainable food production. The CSCB approach also aims to develop and adopt farming techniques and technologies that improve resilience to climate change while simultaneously reducing greenhouse gas emissions and promoting carbon sequestration in agricultural systems. This approach protects and restores biodiversity within agricultural landscapes, as it provides essential ecosystem services that support food production, including services like pollination and natural pest control. At the core of the CSCB approach is the circular economy concept. This concept, which aims to minimize waste, optimize resource efficiency, and promote renewable resources in food production and processing, is a crucial part of the CSCB approach. It encourages us to rethink how materials flow through the food system, engaging us in a commitment to sustainability. Building social equity and justice into the CSCB approach is also essential. Introducing social equity and justice emphasizes the importance of ensuring that food and resources are equitably accessible to all members of society, particularly vulnerable populations. This principle also seeks to address and rectify systemic inequalities within food systems to create a fair and just food system for all.

13.5.1 Integration for Food Security

In the context of food security, resource efficiency plays a critical role in ensuring sustainable agricultural practices. Integrating climate-smart technologies and circular bioeconomy principles aims to enhance resource efficiency in agriculture. This approach focuses on optimally utilizing limited resources such as water, nutrients, and energy to meet the ever-growing food production needs of a rapidly expanding global population. By implementing innovative technologies and sustainable practices, the agricultural sector can significantly improve resource management, leading to more efficient and sustainable food production systems.

In the face of increasing challenges climate change poses, building resilience within the agricultural system is imperative. Adopting climate-smart technologies,

bioeconomy principles, and circular practices plays a crucial role in enhancing the resilience of the agricultural sector. These strategies equip the farm system to withstand the impacts of climate change better, including unpredictable weather patterns and environmental challenges. By integrating these approaches, the agricultural sector can adapt to changing climate conditions and maintain stable food production, bolstering global food security.

A circular bioeconomy approach is a significant contributor to diversifying income sources for farmers. By focusing on creating value from agricultural residues and by-products, farmers can explore new economic opportunities. This approach not only contributes to economic stability for farmers but also promotes sustainable practices by utilizing waste streams as valuable resources. Diversification through circular bioeconomy principles can play a vital role in enhancing the resilience and economic well-being of agricultural communities, thereby contributing to overall food security.

Empirical estimates derived from the implementation of climate-smart technologies, bioeconomy principles, and circular practices are invaluable in guiding policy development and the transition to a CSCB. These estimates, informed by real-world data and experiences, serve as crucial indicators for assessing the impact and effectiveness of sustainable agricultural strategies. In turn, this data-driven approach informs evidence-based policy decisions and facilitates a smooth and informed transition toward a more sustainable and resilient agricultural system.

Various challenges and opportunities warrant consideration in the context of the CSCB. These challenges include the delicate balance between ensuring food security and meeting environmental goals, which often requires weighing trade-offs and considering social, economic, and ecological factors. It is not just crucial but urgent to align and integrate policies across different sectors to avoid conflicts and instead encourage synergies. In addition, fostering collaboration among a diverse range of stakeholders, including farmers, consumers, policymakers, scientists, and civil society organizations, is essential for co-developing and implementing integrated solutions.

Furthermore, leveraging technological advancements such as precision agriculture, biotechnology, and renewable energy can be instrumental in promoting both food security and environmental sustainability. In conclusion, integrating food security and environmental policies is vital for establishing a sustainable and equitable food system. By embracing a systems thinking approach, advocating for sustainable practices, and facilitating stakeholder collaboration, we can envision a future where food security and environmental sustainability complement each other as mutually reinforcing goals.

13.6 The Transition to the Climate-Smart Circular Bioeconomy

In order to establish and promote CSCB practices, it is imperative to focus on the development of interventions aimed at enhancing various processes and mechanisms associated with innovating new products and processes, as well as commercializing them. This involves gaining a deeper understanding of technological advancements through extensive research and development efforts. It should be noted that many novel innovations stem from academic research endeavors. Therefore, to foster the growth of CSCB, it is crucial to make substantial investments in research capacity and human capital, underscoring the pivotal role of policymakers and researchers in this transition.

One of the critical components in promoting CSCB practices is the need for significant investments and a steadfast commitment to change in research and development (Bergman & Rennert, 2024). Additionally, it is essential to develop sound regulations and build capacity for change, particularly in developing countries, to ensure the successful implementation of CSCB practices.

While farmers may perceive the benefits of CSCB practices as relatively minor, they hold substantial value for society. In light of this, policies and regulations that stimulate demand-pull and supply-push are necessary to foster the development of the CSCB production supply chains. Furthermore, social benefit–cost analysis should guide policy and regulation design underpinned by science-based methodologies. These tools should also be continuously updated and improved through benefit–cost analysis, considering regional differences, uncertainties, and random shocks. Valuing natural capital is crucial for accurately measuring social costs associated with CSCB practices.

Education and awareness play a crucial role in promoting the acceptance and adoption of circular bioeconomy products among consumers. By educating consumers about the ecosystem services provided by circular bioeconomy products, policymakers can make them feel the power of consumer awareness. This can lead to a higher willingness to pay, thereby creating a market for circular products and generating political support, making circularity more sustainable in the long run.

Finally, incorporating equity considerations into the processes that support a sustainable and circular bioeconomy is paramount. By prioritizing equity, we can ensure that the benefits of such an economy are distributed fairly among all stakeholders, including marginalized and vulnerable communities.

Despite growth opportunities, businesses and industries face several challenges that can hinder their development. Various market conditions and uncertain economic landscapes can significantly hinder the establishment and operation of new industries and supply chains. These challenges may include unpredictable demand patterns, fluctuating market prices, and volatile economic conditions. In some cases, regulations and policies hinder the adoption and implementation of disruptive technologies that can bring significant benefits. Overly restrictive regulatory rules may lead to slow adaptation to technological advancements and hamper innovation and

progress in various industries. Businesses often encounter location-specific hurdles, such as geographical limitations, infrastructure constraints, and regionally specific regulatory requirements. These factors can impact the feasibility and profitability of operations in different locations, requiring tailored strategies for successful market penetration. In addition to the above challenges, businesses may face other constraints, such as cost pressures, resource limitations, and the need for a global strategy. However, navigating complex political landscapes and addressing geopolitical issues can present obstacles to the development and execution of an effective international strategy. Geopolitical tensions, trade disputes, and diplomatic complexities may hinder the seamless implementation of a unified global business approach.

13.7 Concluding Remarks

In this chapter, we argued that it is crucial to integrate climate-smart technologies and the principles of a circular bioeconomy (i.e., the CSCB approach) to promote sustainable agriculture, improve food security, and mitigate the impact of climate change on the global food system. The CSCB approach, which emphasizes maximizing resource efficiency, minimizing waste, and enhancing the resilience of agricultural practices, has the potential to be an important framework in the future.

It is crucial to approach new technologies and practices with caution, as the decisions we make today will shape the future of agriculture. Many of the technologies and practices we discussed are still in the research and development stage. The potential they hold is significant, but we must rely on thorough research and data to support and illustrate how things unfold. We must employ science-based cost–benefit analysis to either support or reject our null hypotheses, understanding the weight of our decisions in adopting these new technologies.

We need to delve deeper into why farmers need to adopt certain technologies. It is crucial to gain a comprehensive understanding of the specific barriers hindering these technologies' spread. Is it due to our failure to recognize particular technological or practice weaknesses? Or is it because of farmers' lack of awareness and scientific knowledge? Despite some CSCB technologies being available for over a decade, their widespread adoption still needs to be improved. We need to conduct further research to comprehend why stakeholders resist these technologies and whether practitioners should use policy to incentivize farmers, influence behavior, and promote adoption.

We should endorse the statement "let a thousand flowers bloom," and not interfere with the early development of the CSCB. Our cautious approach, guided by scientific data, ensures that we are prepared to stop if the evidence suggests with high confidence that we are on the wrong path. Nevertheless, for now, the authors of this chapter believe we should push the CSCB framework forward.

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Chapter 14
Feedstock Choices for Advancing the Bioeconomy in the US and Policy Implications

Madhu Khanna and Xinxin Fan

14.1 Introduction

Concerns about climate change and the desire to reduce dependence on finite fossil resources have led to growing interest in transitioning to a bioeconomy that utilizes biological wastes and feedstocks to produce bioenergy and bio-based products to displace fossil fuel-based value chains. There is also growing recognition that achieving a target of net zero greenhouse gas (GHG) emissions will require not only displacement of fossil fuels but also removal of carbon from the atmosphere. Soil carbon sequestration on agricultural land offers significant potential to store carbon in soils.

There are various agricultural feedstocks that can be used to produce biofuels, heat, electricity, and bioproducts. These include food-crop-based feedstocks like corn, soybeans, and sugarcane, and non-food-crop-based feedstocks like crop and forest residues, and a range of dedicated energy crops (e.g., miscanthus, switchgrass, energy cane, and others). These feedstocks differ in their yields, land requirements, costs of production, potential for soil carbon sequestration, and carbon intensity relative to each other and across locations. Moreover, these feedstocks also differ in the synergies and trade-offs they offer among various environmental impacts, such as GHG reduction and water quality benefits.

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The production of energy crops and the diversion of food crops for bioenergy raise concerns about their implications for food crop production and for inducing land use change, which can release carbon stocks stored in soil and impact other ecosystems such as water quality and biodiversity (Erb et al., 2012; Vera et al., 2022); the extent to which such effects occur is expected to vary spatially and across feedstocks. The use of food crops such as corn for ethanol has a modest effect on lowering the carbon intensity of fuel, but it increases the use of nitrogen fertilizer, which has a detrimental effect on water quality (Ferin et al., 2021). Energy crops, such as miscanthus and switchgrass, can reduce nitrogen losses relative to row crops (Costello et al., 2009; Smith et al., 2013; VanLoocke et al., 2017), improve soil organic carbon stocks, and lead to negative carbon intensity biofuels, but are costly to produce (Field et al., 2020; Kim et al., 2023). The utilization of crop residues for bioenergy is appealing because it is a by-product of food crop production, relatively low in cost to harvest and does not involve any land use change. However, even low rates of residue removal can have negative consequences for soil carbon stocks and increase nutrient run-off (Battaglia et al., 2021; Cibin et al., 2016; Liska et al., 2014).

Dedicated bioenergy crops have the potential to be grown productively on "marginal" land, leading to the perception that they can be grown without diverting any cropland from food to fuel production. There are various definitions of marginal land, based on productivity, land use, and other physical attributes. Khanna et al. (2021) show that economically marginal land, defined as land that earns a return close to zero with food crop production, is the most likely to be converted to bioenergy crop production because it has the lowest opportunity cost, which is the income foregone from converting land from its most profitable use to an alternative use. Thus, the returns from growing a conventional crop will be foregone if a farmer converts land to an energy crop and will represent the opportunity cost of growing an energy crop. However, they also show that if biomass prices are high enough then even productive cropland (with relatively high opportunity cost) could also have an incentive to switch to producing bioenergy crops. Moreover, other arable non-cropland that is under pasture or grassland may also have an incentive to produce bioenergy crops. This raises normative questions about which type of land should be used to produce bioenergy crops. Conversion of cropland to bioenergy crops can raise food crop prices while conversion of non-cropland to energy crops can have adverse effects on biodiversity and other ecosystem services.

The objective of transitioning to a bioeconomy raises several economic questions. What are the economic drivers of farmers' decisions to produce feedstocks for the bioeconomy? How does the availability of land for bioenergy crop production impact land use choices and feedstock choices for the bioeconomy? What are the synergies and trade-offs among the environmental impacts of feedstock choices? What policy incentives are most cost-effective in inducing the transition to a bioeconomy?

The objectives of this chapter are threefold. First, we discuss economic incentives to produce various biomass feedstocks and the spatial variability in these incentives. These economic incentives vary spatially due to the differences in feedstock attributes, productivity, and land suitability of feedstocks across locations,

which are the key components of costs for producing these feedstocks. Perennial biomass feedstocks also differ in their riskiness, the upfront costs of establishment, and returns over the lifespan of the crop. This can lead to varying incentives for farmers who differ in their risk and time preferences to produce different types of bioenergy crops. The choice of the preferred feedstock to produce at each location will also depend on land availability, the market price of biomass, and the type of policy incentives.

Second, we discuss the multiple environmental impacts of various feedstocks and the land use implications of large-scale feedstock production. Specifically, we discuss the variation in GHG intensity of different feedstocks and the spatial variability in this. We also describe the other environmental impacts of various feedstocks, including their effects on soil carbon stocks and water quality by affecting nitrogen run-off. We discuss the determinants of the types of land likely to be converted for biomass production and its economic implications for food and fuel prices.

Third, we discuss the implications of feedstock attributes for the choice of policy incentives to enable a transition to a bioeconomy and their implications for feedstock and product choice as well as other economic and environmental effects. A variety of policy tools, including mandates, low carbon fuel standards (LCFS), tax credits, and carbon taxes, can be deployed to incentivize feedstock production. These policies differ in the types of feedstocks they will incentivize and their cost-effectiveness in mitigating carbon emissions. Specifically, volumetric biofuel mandates can establish a guaranteed market for biofuels by requiring a specific percentage of renewable content in energy supplies, ensuring consistent demand, while favoring the production of biofuels from the least-cost feedstocks like corn stover. Similarly, a volume-based tax credit, which provides a uniform subsidy for all renewable alternatives without considering their carbon intensity, is likely to only incentivize the use of the least-cost feedstocks. A carbon tax policy, which sets a tax rate based on the carbon intensity of fuels, would incentivize feedstocks that achieve a reduction in carbon emissions most cost-effectively. On the other hand, LCFS programs that assign carbon credits or deficits to a fuel pathway based on the carbon intensity of the biofuel would motivate the production of feedstock-to-biofuel pathways that have the lowest costs of abating emissions to achieve the standard. We discuss the implications of these policy choices for feedstock mix, land use, the costs of carbon abatement, and other environmental impacts.

The rest of this chapter is organized as follows. The next section describes the features of various biomass feedstocks and the spatially varying drivers of the economic incentives to produce them. Section 14.3 describes the environmental impacts of various feedstocks. Section 14.4 describes the effectiveness of various policy incentives and the intended and unintended consequences of these policies, followed by the challenges and opportunities of the bioeconomy in section 14.5 . Section 14.6 concludes with a discussion of future directions for research on the economic and environmental effects of transitioning to a bioeconomy.

14.2 Feedstock Choice and Economics

Biomass for the bioeconomy can be obtained from several sources—dedicated bioenergy crops grown purposefully as feedstocks for the bioeconomy, forest biomass, and agricultural, forest, and food wastes that are used as feedstocks instead of being disposed of in the environment. Dedicated energy crops are appealing because they are high-yielding and can be grown on less productive land with relatively low input requirements. They also have high rates of sequestration of soil carbon and can significantly reduce nitrate leaching relative to conventional crops. Biomass can also be obtained from existing forests that are being used for industrial production of various forest products; the use of forest biomass for bioenergy will need to compete in value with the use of this biomass as pulp and sawtimber. A significant amount of agricultural and forest biomass is in the form of crop and forest residues that are currently not being utilized and are left to decay in the environment. The United States (US) Department of Energy (DOE) estimates that the USA has the potential to produce 1 billion tons of biomass from these agricultural and forestry-based sources (Langholtz et al., 2024).

Dedicated bioenergy crops include perennial grasses—switchgrass, miscanthus, and energy cane—and annual grasses, such as energy sorghum. Residue from corn, corn stover, is also a widely available source of biomass. Switchgrass (*Panicum virgatum*) is a perennial, warm-season grass, native to the tallgrass prairie region, found across most of the eastern and southern USA, with a lifespan of 10 years or more. There are mainly two types of switchgrass varieties: a lowland variety "Alamo" that has thick stems and fits to warm, moist sites in the south of the USA; and an upland variety "Cave-in-Rock" that has thinner stems and tolerates drier soils and cooler weather conditions in the northern USA (Lemus et al., 2014). Miscanthus is a perennial rhizomatous grass with a lifespan of 15 years or more. The sterile hybrid genotype *Miscanthus*×*giganteus* is the most common variety used for biomass, which grows productively in the Midwestern and Northern states of the USA (Ouattara et al., 2020). These perennial crops usually take 1 to 3 years after planting to become fully established and reach the maximum annual yields. Biomass is harvested annually in early spring after the plant senesces in the fall when nutrients translocate to the roots. This reduces the nutrients required for plant growth in the following spring and reduces the moisture content of the biomass, making it more suitable for processing, storage, and conversion. Energy cane is a hybrid cross between sugarcane (*Saccharum officinarum*) that produces thick stems and a related grass species *(Saccharum spontaneum*) that is high-yielding and can be grown in the Southern US states, such as Louisiana and Mississippi (Salassi et al., 2017). Energy sorghum (*Sorghum bicolor* L. Moench, also known as "biomass sorghum") is an annual grass that has higher water use efficiency and drought tolerance than corn and can be incorporated into the existing farming system and managed with standard equipment (Kent et al., 2020; Mullet et al. 2014; Rooney et al., 2007).

Crop residues like corn stover are another promising feedstock option, despite being a low-yielding source of biomass. They are less costly to produce and readily available for farmers to harvest annually as a by-product of planting corn. Corn stover left on the field contributes to soil organic matter and reduces soil erosion. Removal of residues must be restricted to prevent adverse impacts on soil fertility and soil carbon stocks. Previous studies recommend restricting the removal of corn residues to 30% in the case of conventional tillage and 50% with no-till practices in order to avoid negative impacts on corn yield in subsequent years; the removal rate of stover is higher for corn grown with no-till than with conventional tillage because no-till practices leave a larger share of residue on the soil surface while harvesting corn (Scarlat, et al., 2010). Even with these low rates of stover removal, it may be necessary to apply additional fertilizers to replace nutrients that are removed with the stover to maintain soil fertility. Even with these restricted rates of stover removal, there is some loss in soil carbon stocks (Fan et al., 2024). We now describe and compare the yields, costs, and breakeven prices at the farm gate of producing different types of feedstocks. The breakeven price is defined as the minimum price per dry metric ton of the bioenergy crop that would result in a return equal to the foregone return from converting land to produce the energy crop. In the case of a perennial energy crop, which has a stream of costs and revenues over its lifespan, a breakeven price is the one that equates the net present value of its costs of production (including the opportunity cost of land) to the net present value of revenue from its production over the life of the crop.

14.2.1 Biomass Yields

Field experiments with these energy crops provide data that has been used to parameterize biogeochemical models, such as the DayCent model (Daily CENTURY). Simulated yields from the DayCent model show that biomass yield varies substantially across feedstocks and across regions for each of the feedstocks. Miscanthus typically has the highest yields across locations in the US rainfed region, with median yields ranging from about 12 to 20 metric tons per hectare (MT per ha) per year, followed by energy sorghum with median yields ranging from about 13 to 17 MT per ha per year. Switchgrass yields are the lowest and least variable across locations and the median yields range from 9 to 14 MT per ha per year. Energy cane has yields of 18 to 20 MT per ha per year. The yields of corn stover are much lower than that of energy crops and differ depending on the rotation and tillage practices across locations, which is the highest in the Midwest under the corn-soybean rotation with no-till. These lead to variability in the costs and land use requirements for producing a feedstock in a location and heterogeneity in relative performance of feedstocks across locations.

14.2.2 Biomass Breakeven Price

The breakeven price of an energy crop at the farm gate is the minimum price ($ per MT) needed to incentivize landowners to convert cropland to an energy crop while that of corn stover is the minimum price needed to induce harvesting of corn stover. The feedstock breakeven price includes the costs of fertilizer, seeds, and chemicals; costs of planting, costs of hauling, storage, and transporting biomass to processing facilities during harvest years. In the case of energy crops, this includes the opportunity cost of converting land and foregoing returns from its best alternative use. Since perennial energy crops, miscanthus and switchgrass, require high upfront costs of establishment (such as costs of land preparation and planting) and provide yields during the establishment years differing from those over the remaining lifespans of these crops, the discounted net present values of the sequence of annual costs and yields over the life of each perennial crop are calculated to obtain the breakeven price. For energy sorghum and corn stover, the costs of production and yield are on an annual basis. The breakeven price of a crop is then the price per metric ton of dry matter needed to cover all the discounted present value of costs of production incurred over the lifetime of the crop. The costs of collecting corn stover include the additional cost of fertilizer that needs to be applied to replace the loss of nutrients and soil organic matter due to the removal of the crop residues from the soil, and costs of harvesting stover (i.e., mowing, raking, baling, staging, and storage).

The farm-gate breakeven price can vary across feedstocks and locations, due to the spatial heterogeneity in feedstock yield, land feasibility, and the opportunity costs of land for energy crops. Fan et al. (2024) simulate the breakeven prices of producing four cellulosic feedstocks (miscanthus, switchgrass, corn stover, and energy sorghum) at the 4 km resolution of the US rainfed region, considering the spatial varying yields and costs of feedstock production. They show that the lowest breakeven price of producing miscanthus as a feedstock is found in the Midwest, switchgrass in the Southeast region, and energy sorghum in the Great Plains; while that of corn stover is lower than that of energy crops across locations because the effect of lower costs of corn stover production outweighs that of a lower biomass yield of stover harvesting.

14.2.3 Potential Feedstock Supply and Mix

The USA currently uses about 342 million tons of biomass in 2022 to generate 5% of the nation's energy; of this, 163 million dry tons are agricultural biomass, 144 million dry tons are forest and woody biomass, and 37 million dry tons of biomass come from waste resources (Langholtz et al., 2024). The primary biomass sources in the current bioeconomy are corn grain for producing ethanol for transportation and forestry/wood and wood waste for heat and power. As projected by the 2023

Billion-Ton Report, the USA has the potential to produce an additional 800–1200 million tons of biomass per year. The largest growth is contributed by the adoption of energy crops, accounting for 40% to 55% of that additional biomass availability.

14.2.4 Economic Incentives for Biomass Feedstock Production

The production of biomass for biofuels and other bioproducts is influenced by a variety of factors, including land availability, biomass price, policy incentives, and farmer's risk and time preferences. We now discuss these factors based on a review of the existing literature.

Land Availability While economically marginal land is the most likely to have the economic incentive to produce energy crops, the availability of this land varies spatially and over time (since it is dependent on the returns to land which can depend on market conditions) and identifying this land at fine spatial resolution is challenging in the absence of economic data on returns to land. Jiang et al. (2021) use high resolution satellite data on land use change to infer that land that is frequently transitioning between crop and non-crop is economically marginal land. They found that the amount of land that can be classified as marginal with certainty in the USA is relatively small and that there is a substantial amount of land that can only be classified as marginal with uncertainty. In addition, the production of energy crops may not be limited to marginal land because cropland and other non-cropland can also have an economic incentive to convert to energy crops, depending on biomass price and policy incentives, suitability of land for alternative crops, and availability of various types of land. Moreover, surveys show that farmers are often reluctant to convert their non-cropland, which is providing various ameneties, such as open space, wilderness or hunting and other uses, to energy crops (see Khanna et al. (2021)).

Conversion of cropland to energy crops raises concerns about its impact on food crop prices, while conversion of non-cropland to energy crops raises concerns about the loss of carbon stocks in the land due to land use change, and whether this would be smaller than the savings in carbon emissions due to the production of bioenergy. These concerns can lead to restrictions on the type of land that can be used to produce bioenergy crops. The type of land that is allowed to be converted to bioenergy crops will affect the economic and environmental impacts of bioenergy production. Restricting production to cropland will limit the amount of biomass production and result in a higher biomass price being needed to achieve a given level of biomass production because of the high opportunity cost of converting that land to bioenergy crops.

Biomass Price The price of biomass will affect the profitability of producing biomass and the mix of feedstocks produced. A low biomass price can be expected to primarily lead to incentives to harvest corn residues from existing land under corn production. It can also lead to conversion of land from corn-soybean rotation to

continuous corn in order to increase the supply of corn stover. As biomass price increases, it will create incentives to harvest crop residues and then produce energy crops on lower cost non-cropland in the areas most productive for specific energy crops; biomass prices would need to be quite high for energy crop production to be economically viable on cropland.

Input Prices The prices of inputs for biomass production are crucial for both the economic viability of biomass and the overall development of the bioeconomy. Production of feedstocks requires various inputs including rhizome, seed, fertilizer, and chemicals, and fuel and machinery. Prices of these inputs will affect the costs of biomass production while the extent of their effects varies across feedstocks. For perennial feedstocks, such as miscanthus and switchgrass, the costs for crop establishment in the first year are the highest and different from those in subsequent years, because they include the costs of land preparation and planting to establish the crop. The costs of rhizomes account for the largest share of the establishment costs (Winkler et al., 2020). For corn stover, the cost of applying additional fertilizers to replace the nutrients that are removed with the stover and the cost of machinery for harvesting operations are the primary components of the total production cost (Thompson & Tyner, 2014).

Opportunity Cost of Land The opportunity cost of land is the profits that are foregone by a landowner who converts land to produce a bioenergy crop instead of its most profitable alternative use. In the Midwest, the opportunity cost is usually measured as the difference between the per-hectare revenues from a corn-soybean rotation and its costs of production, because the corn-soybean rotation is the dominant cropping practice (Khanna et al., 2008; Jain et al., 2010). The opportunity cost of land is particularly high in locations where the yields of corn and soybeans are high while the costs of their production per hectare are relatively low.

Risk and Time Preferences of Farmers The high upfront costs and establishment lags involved with the production of energy crops, such as miscanthus and switchgrass, require farmers to trade off future returns for current costs. Incentives to convert land from conventional row crops to energy crops will differ in farmers' risk, time, and uncertainty preferences and the accessibility to financial support that can cover the upfront costs of establishment. The risks and returns from producing crop residues and energy crops are spatially varying across feedstocks due to the differences in agronomic characteristics of their production, land suitability, and growing conditions for these crops. The farmer's choices of whether to produce a feedstock, which perennial bioenergy crop to produce, and how much land to use for it, given differences in their riskiness and lifespan, will depend on their risk-aversion and time preferences.

Previous research has shown that energy crops with long establishment periods, high establishment costs, and uncertain yields due to weather variations, reduce incentives for producing them for risk-averse and present-biased farmers. This is

particularly the case for credit-constrained farmers because they are unable to obtain a loan to pay off the upfront costs of producing energy crops through annualized payments; the need to bear the entire upfront costs of planting an energy crop leads to a large variation in returns over the lifespan of the crop (with large negative returns in the early years and positive returns in later years), and this increases the riskiness of producing them. Farmers with high discount rates may be less willing to produce perennial energy crops, due to their long establishment periods and high establishment costs (Miao & Khanna, 2017a, 2017b). Majeed et al. (2025) examine the effect of farmer risk-aversion, time-discounting, and access to credits on the potential production and mix of cellulosic feedstocks (miscanthus, switchgrass, and corn stover harvest). They find that risk-averse, present-biased, and credit-constrained farmers will prefer to grow the low-yielding but less risky energy crop switchgrass instead of miscanthus while the less risk-averse farmers with lower discount rates and no credit constraints will prefer to grow miscanthus.

Availability of Crop Insurance Farmers producing conventional crops in the USA typically have access to subsidized crop insurance as a risk-mitigating tool. In the absence of a similar insurance program for energy crops, they face greater risk in converting land from conventional crops to energy crops. Miao and Khanna (2017a) show that this disincentive is larger for farmers with low discount rates who put greater weight on yield risks over the lifespan of the energy crop as compared to farmers with high discount rates who care more about upfront costs.

Contractual Arrangements and Location of a Biorefinery Biomass is high volume and low density and costly to transport long distances. Proximity of feedstock production to a biorefinery and the capacity of the biorefinery will influence the price the refinery is willing to pay for biomass and the incentives to convert land to produce it. Additionally, there are several options for the types of contracts a biorefinery may offer farmers. Biorefineries can offer to lease land from the farmer and produce the energy crop themselves; taking on all the risks themselves and offering the farmer a risk-free option. Alternatively, they could pay a fixed biomass price to the farmer or a fixed share of the profits from the feedstock production and refining process. A fixed biomass price eliminates the price risk for the farmer but exposes them to yield risk. A share in the profits would imply that the farmer shares in the upside and downside risk of producing feedstocks. Yang et al. (2016) show that a farmer's choice of contract will depend on their degree of risk-aversion, time preferences, and land quality.

Availability of Workforce The stable availability of a well-trained workforce is crucial for efficient and safe refinery operations, as the industry requires highly skilled personnel with expertise in process engineering, maintenance, and safety protocols. Refineries face challenges in finding and retaining experienced workers due to an aging workforce, competition from other industries, and the need for continuous training to keep up with technological advancements (NRC, 2015). Investing

in apprenticeship programs, partnerships with technical schools, and ongoing professional development can help ensure a steady pipeline of qualified workers.

14.3 Environmental Effects of Feedstock Production

Biomass feedstock production has multi-dimensional impacts on the environment that can differ from those of conventional crops. These impacts vary across feedstocks and across locations (Fan et al., 2024). We focus here in particular on the effects of these feedstocks on GHG emissions and nitrogen run-off.

GHG Effects Biomass feedstocks affect GHG emissions through three main ways: life-cycle emissions which account for all the emissions generated during the process of feedstock production from planting to harvest and delivery to a biorefinery; direct effects on soil carbon stocks due to the feedstock; and indirect effects on soil carbon stocks due to the price changes caused by the diversion of land from other uses to feedstock production. Energy crops have the potential to produce low to negative GHG intensity biofuels, because they are produced under rainfed conditions, have low fertilizer requirements compared to corn, high carbon sequestration rates, and generate electricity as a co-product during their conversion to biofuels in a cellulosic biorefinery. Since different energy crops differ in their yields, input requirements, and lifespans, and in their effects on soil carbon, they differ in their GHG intensity. Moreover, these drivers of GHG intensity differ across locations for a given feedstock. The indirect land use change emissions caused by diversion of cropland for energy crop production will depend on the type of land (marginal land or cropland) on which these crops are grown. The GHG intensity of crop residue-based biofuels, on the other hand, is higher because they may require replacement nitrogen applications to maintain soil fertility and because residue removal has a negative impact on soil carbon stocks (Dwivedi et al., 2015; Fan et al., 2024; Lee et al., 2023). Fan et al. (2024) provide estimates of the GHG intensities of crop residues and various energy crops in the rainfed region of the USA. Lee et al. (2023) show that the induced land use change (ILUC) related GHG intensity of a mix of cellulosic biofuels is lower than that of corn ethanol, due to the higher yields of biomass feedstocks and their potential to grow on lower quality land. It should be noted that technological uncertainties are particularly important when evaluating the potential of advanced biofuels to reduce GHG emissions, because advanced biofuels have yet to be produced at a commercial scale, which in turn makes it more challenging to validate the extent to which different assumptions and biorefinery designs would be reliable and feasible, compared to food-crop-based biofuels.

Water Quality Effects Bioenergy feedstocks differ in their impacts on nitrogen run-off and leaching, which can affect surface water and groundwater quality. The use of food crops for biofuels, particularly corn which is not only carbon intensive but also nitrogen intensive, can worsen water quality problems. Expansion of corn

ethanol production has also been shown to exacerbate nitrogen run-off through the Mississippi Atchafalaya River Basin (MARB) and worsen hypoxia in the Gulf of Mexico (Ferin et al., 2021; David et al., 2010; EPA, 2018). On the other hand, perennial feedstocks have lower impacts on nitrogen leaching because they do not require annual tillage operations, have larger root systems, and require lower fertilizer application relative to annual crops. Previous studies have shown that replacing row crops with miscanthus or switchgrass can reduce nitrogen leaching by 10%–24% at the watershed scale (Mishra et al., 2019; Valcu-Lisman et al., 2016). Vanloocke et al. (2017) found that if switchgrass or miscanthus were to displace 40% of land currently under corn production, the nitrogen loss in the MARB would decline by 20% and 25%, respectively. The harvest of corn stover, on the other hand, could lead to nitrogen run-off and worsen water quality (Ferin et al., 2021), particularly if it is accompanied by the application of replacement nitrogen fertilizer to maintain soil fertility.

14.4 Policy Incentives for Cellulosic Biomass Production

Cellulosic biofuels can provide energy with a lower GHG intensity for the transportation sector relative to food crop-based ethanol, but their costs of production are high. Hence, federal and state policy incentives are needed to induce their production and blending with gasoline. These incentives have taken various forms, such as volumetric tax credits and biofuel mandates at the national level and LCFS and tax exemptions and deductions at the state level. Biofuel mandates, in particular, have been a widely deployed policy across the world, with over 80 countries having established blending mandates (IEA, 2025). In the USA, the Renewable Fuel Standard (RFS), established by the Energy Independence and Security Act (EISA) of 2007, set volumetric goals for different types of renewable fuels to be blended into transportation fuels. While it was effective in inducing the production of corn ethanol to over 15 billion gallons, of renewable diesel fuel to 2.6 billion gallons, and of biodiesel to 1.7 billion gallons by 2023, its 16-billion-gallon cellulosic ethanol mandate has not been effective in inducing large-scale production of cellulosic biofuels as envisioned (EIA, 2025). Cellulosic Waiver Credits (CWCs) under the RFS provide obligated parties to meet their obligations of cellulosic biofuel production through purchasing waiver credits (Zhong & Khanna, 2022). The RFS has set threshold levels of carbon intensity (including life-cycle emissions and direct and indirect land use emissions) for various types of biofuels and volumetric standards. This does not create incentives to produce high-cost biofuels with carbon intensity lower than the threshold level for compliance. Instead, it creates incentives to produce the lowest-cost biofuel that complies with the standard.

Similar to a biofuel mandate, the volumetric tax credit will also induce production of the lowest-cost feedstock pathways. It explicitly subsidizes biofuels and does not penalize fossil fuels; hence, it is likely to lead to lower blending rates than a blend mandate. The US Treasury's Section 40B tax credit offered incentives for

Sustainable Aviation Fuel (SAF) that can achieve a minimum GHG emissions reduction of 50% over 2023–2024. In 2025, the US Treasury released Section 45Z Clean Fuels Production Credit for all transportation fuels and intends to propose rules for it that will incorporate the carbon benefits from feedstocks produced with climate-smart practices. The LCFS is a performance-based standard to reduce the GHG intensity of transportation fuels. It currently does not exist at the national level, but has been established in states including California, Oregon, Washington state, and New Mexico. It provides a differentiated implicit subsidy for a biofuel fuel based on its carbon intensity relative to the desired intensity standard and implicitly taxes fossil fuel depending on the extent to which its carbon intensity exceeds the LCFS. An LCFS creates incentives to blend biofuels with the lowest cost of GHG abatement, but like the RFS it also cannot guarantee a reduction in GHG emissions. Fan et al. (2024) show how these policies will differ in the incentives they offer for different biomass feedstocks and how they affect the spatial mix of feedstocks that are produced in the rainfed region. Huang et al. (2013) examine the economic and GHG implications of stacking a national LCFS with and without a carbon price policy on the RFS. They find that combining the RFS with an LCFS policy will reduce the production of the first-generation biofuels while increasing the second-generation biofuel production relative to the RFS alone, along with a greater GHG emissions reduction in 2035.

Besides state-wide clean fuel standards like LCFS, there is an increase in the adoption of other types of state policies, including tax incentives and infrastructure grants to motivate the production and utilization of biofuels. Stewart et al. (2023) evaluate the efficacy of 20 state-level tax incentives from 14 states, such as tax exemptions based on a biorefinery's capital investment, and tax credits determined by the amount of biofuel the biorefinery produces. Their findings support the role of tax incentives in improving the financial viability of biorefineries. However, the efficacy of different tax incentives depends on various factors such as the specifications of the incentives themselves and the duration for which the incentive is provided. Moreover, many US states have enacted either Renewable Portfolio Standard (RPS) or Clean Energy Standard (CES) to increase the use of cleaner electricity by either requirements or goals for electricity providers to supply a specified percentage (or absolute amount) of customer demand from low- or zero-carbon emission sources (EIA, 2024). However, relative to state-level policies, implementing policy incentives at the national level to reduce GHG emissions is considered more efficient, as it allows flexibility in achieving GHG mitigation through the least-cost approaches across all sectors and regions within a country. Oliver and Khanna (2018) show that a hypothetical national RPS can induce the same share of electricity generated from renewable sources as the state RPSs at a lower welfare cost over the 2007–2030 period. The national RPS will achieve greater GHG savings than the state-level RPSs by inducing a higher reduction in coal generation.

Policies such as biofuel mandates and even the LCFS or carbon intensity based tax credits may incentivize low-carbon-intensity biofuels but can exacerbate nitrate run-off by expanding nitrogen intensive feedstocks. The objective of reducing multiple environmental externalities, GHG emissions and nitrate run-off, will require a

policy targeted at each externality. Fan et al. (2025) show that to achieve the desired GHG emissions reduction and nitrate run-off reduction it will be necessary to supplement biofuel mandates with a carbon tax and a nitrate tax. The magnitude of these taxes will depend on the type of biofuel mandate in place. A corn ethanol mandate will need to be supplemented with a higher carbon tax and nitrate tax to achieve a given level of reduction in GHG emissions and nitrate emissions as compared to those with a corn ethanol mandate combined with a cellulosic ethanol mandate.

14.5 Challenges and Opportunities

Though bio-based energy and products and related industries can provide multiple economic and environmental benefits and opportunities to progress toward a bioeconomy, scaling up the production of biofuels and bioproducts in biorefineries is still restricted by feedstock availability, environmental and social concerns, immature technology, high production costs, and policy uncertainty (Chen & Smith, 2017; Rathour et al., 2023). Perennial energy crops have the potential to not only provide bioenergy that can reduce dependence on fossil fuels but also reduce GHG emissions and nitrate run-off relative to conventional crops. However, production of these feedstocks requires markets for biofuels, bioenergy, and bio-based products that can be produced with these feedstocks; the production of these products requires large investments in refineries as compared to first-generation feedstocks and fossil fuels.

Biomass Supply Chains Biomass logistics operations, including biomass harvesting and collection, storage, transportation, and preprocessing of biomass, fundamentally impact the economic viability and sustainability of the bioeconomy. Logistics costs in some cases can account for 90% of the total feedstock cost (Malladi & Sowlati, 2018). Optimizing biomass logistics is complex because of the characteristics of biomass such as its seasonal availability, vulnerability to climate, scattered geographical distribution, and uncertainties in biomass quality and composition (Caputo et al., 2005). Given the high cost of long-distance transportation and biomass degradability, the location of biorefineries is usually constrained to areas where there is a sufficient and stable biomass supply within a certain distance. In turn, the presence of a biorefinery impacts farmers' planting decisions. Hence, it's important to diversify the biomass demand markets, such as developing new applications for biomass beyond energy production (e.g., bioplastics for packaging) to reduce farmers' risk associated with relying on single-use cases. Additionally, the cultivation of oilseeds (e.g., pennycress and camelina) as cover crops or through double-cropping can increase feedstock availability for biodiesel and SAF without inducing land use change (USDA, 2024).

Conversion Technology Biomass is a naturally complex and heterogeneous resource, composed of diverse components such as cellulose, hemicellulose, lignin, and a wide array of organic compounds, each with distinct chemical, physical, and structural properties. These unique characteristics present not only significant opportunities for innovation to produce a broad spectrum of high-value products like biofuels, bioplastics, and biochemicals that can replace fossil-based products or create a new market, but also substantial challenges for current technologies, which often encounter difficulties in efficiently separating and convert these components into products (Chandel et al., 2020; Rathour et al., 2023). As a result, the full potential of biomass remains underutilized, constraining the economic viability and environmental sustainability of bio-based industries. In addition, biomass conversion usually involves multi-step processes, and each of which requires different conversion mechanisms involving advanced technologies and necessitating the use of expensive catalysts to improve conversion efficiency, which, as a result, increases the costs at biorefineries and limits the scalability of production (Pascoli et al., 2022). According to Davis and Bartling (2023), several strategies, such as optimizing the feedstock preprocessing and fermentation, integrating the enzyme production equipment with the biorefinery to improve resource (e.g., land and infrastructure) utilization, and creating an integrated processing pathway including lignin deconstruction and conversion to coproducts, offer great opportunities to increase conversion efficiency and reduce costs at biorefineries, thereby improving the financial viability of bioenergy and bioproducts against their fossil-based alternatives. Advancements in biotechnology, particularly in conversion technology, are poised to revolutionize the bioindustry. They will enable more efficient, cost-effective, and sustainable conversion processes with a diversified product portfolio to meet growing demand for various eco-friendly alternatives, ultimately unlocking new economic and environmental opportunities across sectors. Furthermore, investment in biorefineries is risky for the private sector in the absence of assured policy induced demand for bio-based energy and bioproducts. The high costs of these bio-based products relative to fossil fuels and the duration of time needed to lower costs through learning by doing and economies of scale imply that policy incentives will need to be sustained for a long duration.

Markets for Biofuels and Bioproducts The markets for biofuels and bioproducts are experiencing significant growth, driven by increasing demand for sustainable alternatives to reduce emissions and supportive policy incentives. High-blend vehicles, such as Flex-Fuel Vehicles (FFVs) designed to run on gasoline or gasoline-ethanol blends of up to 85% ethanol (E85), offer a viable path toward decarbonizing transport, but factors like gasoline price, limited refueling infrastructure, and consumer awareness and acceptance pose significant barriers to widespread adoption. SAF is expected to be one of the primary growing biofuel markets in the next decades, while the high production cost remains the key barrier to scale-up of SAF production (IEA Energy, 2023). The production of bioproducts has also attracted considerable attention for commercialization due to the high market prices of chemical compounds. Bioproduct production could use less energy and emit less GHG

than that of their fossil-based counterparts (Dunn, 2019; Huang et al., 2021). However, fossil-based chemicals are widely used over bio-based chemicals because currently the costs of producing bio-based chemicals in many cases exceed those of petrochemical products (IEA, 2020; USDA, 2024b).

Regulatory Incentives The advancement of the bioeconomy is also heavily dependent on public policies and regulations across the world. Policies or regulations that lack clarity or are prone to frequent changes create significant challenges for investment and long-term planning in biomanufacturing and biomass feedstock supply systems. For example, biomass supply chain systems may be affected by policies in land use, forestry management practices, agricultural marketing policies, biofuel mandates, and biotechnology regulatory requirements. This complex and overlapping regulatory framework may make it difficult for stakeholders to navigate and ultimately discourage investment and innovation. Other programs and policies, like loans, grants, and tax incentives, can promote innovation, but their effectiveness may be limited if they are not available consistently over the long term or fail to match the magnitude of the capital investments needed (Makepa & Chihobo, 2024; Salvador et al., 2022). Therefore, for stakeholders related to bio-based industries, a stable and predictable policy and regulation framework is crucial to mitigate risks and foster innovation and participation in markets. Long-term policy stability can also help farmers and forest landowners justify investments particularly in perennial production systems that require significant upfront costs and time for establishment while providing a productive lifespan of a decade or more. While performance-based policies, such as a carbon tax or an LCFS, will be the most cost-effective in inducing the mix and quantity of biomass feedstocks that can reduce GHG emissions, these policies raise concerns about their impact on fuel prices. The impact of these policies can be regressive and fall disproportionately on lower income households for whom energy costs are a larger share of expenditure than for higher income households.

Workforce Education and Public Awareness Increased education and awareness about the benefits of transitioning to a bioeconomy are needed to build public support for the transition. The lack of a stable, trained workforce poses a significant challenge to refinery operations, particularly as the industry shifts toward more advanced biotechnological processes. Hence, prioritizing workforce development through specialized training programs and hands-on training initiatives and enhancing collaboration with academia and government will be crucial to bridge this skills gap and ensure the long-term sustainability and growth of the biorefining sector. Large-scale feedstock production can be expected to divert marginal land and cropland from existing uses. The diversion of cropland for high-yielding energy crop-based biofuels has the potential to raise food crop prices, although to a lower extent than the diversion of food crops for a similar volume of biofuels. The diversion of non-cropland to crop production induced by the demand for feedstocks raises concerns about the loss of ecosystem services and soil carbon stocks. These concerns

affect public opinion about the transition to a bioeconomy and create a perception of conflict between food and fuel production.

14.6 Conclusions

The sustainable supply of economically viable biomass from high-yielding feedstocks is critical to make a transition to a bioeconomy that uses bioenergy, biochemicals, and other bio-based products, to decarbonize the US transportation and industrial sectors. Economic costs and returns and environmental impacts of biomass production differ across feedstocks and across spatial locations due to heterogeneity in feedstock attributes, land suitability and growing conditions for different feedstocks, opportunity costs of land in the case of dedicated energy crops, and soil carbon effects. Perennial energy crops can produce high biomass yields even on low quality land due to their low requirements for input resources and maintenance and have longer lifespans exceeding a decade for biomass production, relative to annual crops and crop residue. They can also provide diverse environmental benefits such as sequestering carbon in soil and reducing nitrogen leaching.

However, the production of these bioenergy crops involves high upfront costs and a long period for establishment, and thus requires a long-term land commitment and is more likely to impose higher risks than annual crops. Policy incentives will play a crucial role in motivating the choice of growing perennial energy crops, such as the Biomass Crop Assistance Program in the USA, which offers payments that partially cover the establishment costs for perennials through a cost-share program (Miao & Khanna, 2017b). Additionally, land availability, biomass price, and farmers' preferences for risk, time, and uncertainty preference together with policy support will affect the mix of preferred feedstocks.

A wide range of products can be derived from biomass, including biofuels, biochemicals, bioplastics, and other renewable materials, highlighting their versatility and potential for sustainable innovation. The literature has shown that with optimized biomass supply chain systems and improved conversion technologies and process designs, non-food-crop-based feedstocks like perennial energy crops can be used to produce biofuels and bioproducts that are economically competitive with their fossil-based counterparts, therefore, their high potential for sustainability can be effectively leveraged to drive long-term environmental, economic, and social benefits, fostering resilient and regenerative systems. However, the current bioeconomy still faces several challenges across its entire supply chain, from biomass sourcing to end-product delivery, including insufficient availability of suitable feedstocks, the inherent variability of feedstocks in composition, moisture content and energy density, immaturity of bioconversion technologies, and uncertainty from policies and regulations. Strategies to improve the sustainability and economics of agronomic practices, harvesting and logistic systems, advance biorefinery technologies, and establish clear, stable, and consistent policy frameworks can help address these challenges, while highlighting key areas for further research and development to continuously accelerate the transition toward a bioeconomy.

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Chapter 15
Biotechnology and Microbial Genomics for Circular Bioeconomy

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15.1 Circular Bioeconomy

Worldwide industrialization is linked with an increasing demand for energy and natural resources, the consumption of fossil fuels, high pollution, and greenhouse gas (GHG) emissions, which are associated with climate change. The circular economy emerges in response to the traditional linear economy, which extracts raw materials from nature, manufactures products, and finally throws them away as waste. The circular economy improves the sustainability of goods and services and minimizes waste (Stahel, 2016; Ubando et al., 2020). Furthermore, a study indicates that a transition of a European nation to a circular economy could decrease up to 70% greenhouse gas (GHG) emissions and increase by 4% its

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workforce (Stahel, 2016). In this century, biomass has been promoted as an alternative to fossil fuels to fulfill the requirements of society. The biorefinery of biomass, which generates multiple products from biological feedstocks, resembling the refinery of petroleum in the fossil-fuel-based economy, is of increasing application toward the bioeconomy (Ubando et al., 2020). The term bioeconomy has

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been defined as "the production, utilization and conservation of biological resources, including related knowledge, science, technology, and innovation, to provide information, products, processes, and services across all economic sectors aiming toward a sustainable economy" (International Advisory Council of the Global Bioeconomy Summit (IACGBS), 2018). The bioeconomy is growing worldwide, generating in 2019/2020 more than 17.5 million direct jobs in the European Union and >2.5 million direct jobs in Argentina (Trigo et al., 2023). Bioeconomy is strongly associated with the United Nations (UN) Sustainable Development Goals (SDGs). The circular bioeconomy is based on biological resources that are transformed into services, processes, and products, which are later recycled with minimal waste accumulation and environmental impact (Fig. 15.1). The feasibility of the circular bioeconomy relies on the available resources, ecosystems, and socioeconomic aspects (e.g., sustainable production

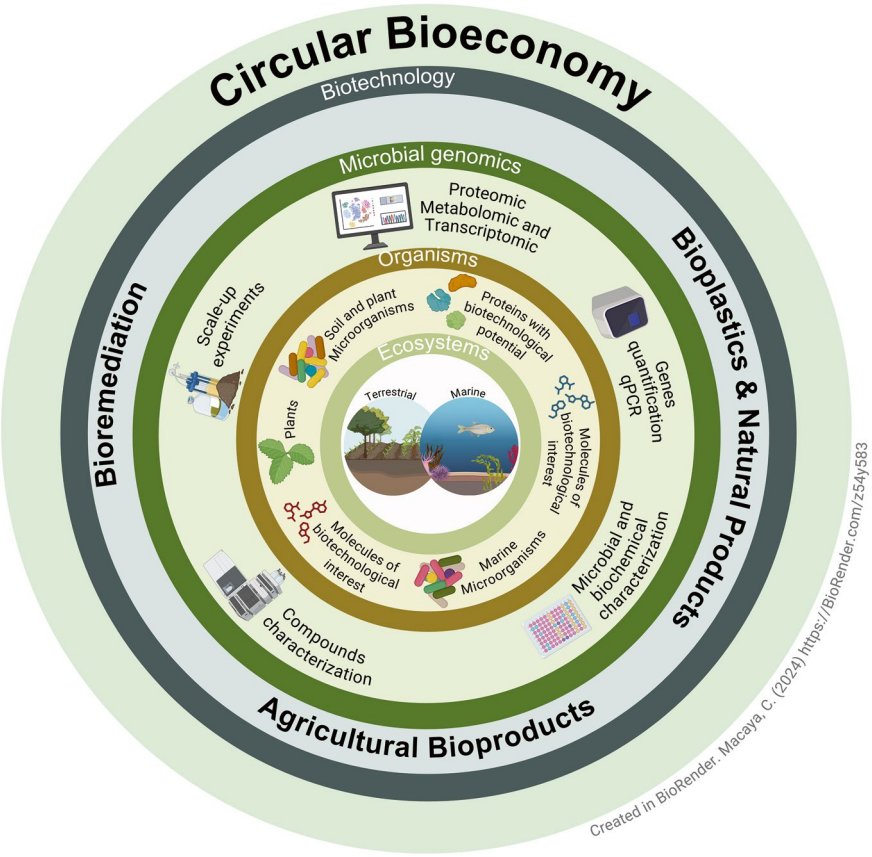

Fig. 15.1 The journey from biodiversity resources through their molecular characterization supported by genomics to their biotechnological applications for circular bioeconomy. Graphical representation of the different levels: 1) ecosystems, 2) organisms, 3) techniques (dry lab and wet lab), and cross-cutting disciplines, such as microbial genomics, 4) development of various biotechnological fields, including bioremediation, agricultural bioproducts, bioplastics, and natural bioproducts development, following sustainability principles, and 5) circular bioeconomy, a more efficient and environmentally friendly economic model

and consumption, economic growth, trade, services, poverty and inequality reduction, job creation) at a regional or local level (Food and Agriculture Organization of the United Nations (FAO), 2018). Bioeconomic clusters located in several European countries have demonstrated the ability to promote circular schemes, improving the manufacturing of bio-based products (e.g., bioplastics, biofuels) (Stegmann et al., 2020). The bioeconomic sector in Germany has grown 22% from 2002 to 2010, contributing to 6% of the overall economic value in 2010 (FAO, 2018).

15.2 Biotechnology

The development of human society has been based on the use of living organisms and biological processes to improve the quality of life. Key steps for the development were the domestication of animals and plants and the use of plant, animal, and microbial natural products for medicine. The history of biotechnology could be classified in different eras (Smith, 2009; Rennenberg et al., 2016). Classical biotechnology includes the fermentation processes for bread and beverage production more than 8000 years ago. In a second era of biotechnology that began at the end of the nineteenth century, diverse biotechnological processes under non-sterile conditions were developed such as urban wastewater treatment, urban composting of solid wastes, and the synthesis of diverse products (e.g., ethanol, acetic acid) by microbial fermentation. Production of antibiotics, enzymes, vaccines, and other biotechnological products under sterile conditions originated in the 1940s in the third phase of biotechnology. The revolution of modern biotechnology started with genetic engineering in California in 1973 by Stanley Cohen, Paul Berg, and Herbert Boyer. Modern biotechnology employs cellular and molecular processes including genetic engineering to develop technologies, products, and services that contribute to the advancement of the society and environmental protection, promoting sustainable development (Smith, 2009; Rennenberg et al., 2016).

The markets of several areas of biotechnology are growing. Environmental bioremediation reached a global market of 186.3 billion in 2023 (Orellana et al., 2022). Sustainable agriculture reached a market of USD13.5 billion in 2023 (The Business Research Company, 2024). Biotechnology associated with human health, which includes the production of antibiotics and biomaterials, had a global market size of USD385 billion in 2023 (Precedence Research, 2024).

Microorganisms (e.g., bacteria, fungi, yeasts, archaea) play a key role in the development of biotechnology and participate in diverse fields such as industry, medicine, agriculture, environmental decontamination, and novel materials. The huge metabolic diversity of microorganisms is crucial for biotechnology (Palmerín-Carreño et al., 2015; Rennenberg et al. 2016; Orellana et al., 2018). Microorganisms contribute significantly to global sustainable development, for example, supporting the search for novel added-value materials and compounds for human health and crop protection, the restoration of contaminated ecosystems and their use in the development of molecular analytical methods (Rennenberg et al., 2016).

Environmental biotechnology is defined as a discipline that applies biological systems and processes to address environmental challenges such as waste

management and the clean-up of polluted sites (Smith, 2009; Orellana et al., 2022). Environmental biotechnology involves the development, use, and regulation of biological systems (e.g., microorganisms, plants) and processes (e.g., bioremediation, phytoremediation) for the restoration of contaminated ecosystems (soil, water, and air) and decreasing environmental impacts of industrial processes (Zylstra & Kukor, 2005; Orellana et al., 2022). Environmental biotechnology has revolutionized the agricultural, industrial, and environmental sectors. Next-generation industrial biotechnology has developed tools based on the diversity of microorganisms (e.g., halophile, acidophile biocatalysts) to produce a wide range of bioproducts in processes that minimize costs, water, and energy usage and environmental impacts (Yu et al., 2019). However, scalability and optimization are ongoing challenges that increase the cost of bioproducts (Orellana et al., 2018, 2022; Alvarez-Santullano et al., 2021; Undabarrena et al., 2021). To innovate in the processes and services that environmental biotechnology offers, a responsible use of the resources involved is required to minimize environmental impact throughout the lifecycle of the developed products and processes, directly relating to the principles of the circular bioeconomy (Sarvatli, 2017; Lokko et al., 2018; Schwartz Melgar et al., 2022).

Environmental biotechnology contributes to main dimensions in the development of the circular bioeconomy: 1) Closing material cycles, through the design of processes for the reuse/recycling of materials and waste, 2) Pollution reduction and restoration of contaminated sites, by developing technologies and processes to clean-up soil and water, and 3) Development of sustainable products, manufacturing products with a prolonged useful life and that are recyclable (Aguilar et al., 2019; Orellana et al., 2022).

Policies on the development of knowledge in biological resources and worldwide scientific collaboration were crucial for the circular bioeconomy development of the European Union, the United States of America, and China (Patermann & Aguilar, 2018; Wohlgemuth et al., 2021). Advances in emerging research topics such as the information technologies have allowed the emergence of omics technologies (e.g., genomics, transcriptomics, proteomics, metabolomics) providing a deep understanding of biological systems, which has been pivotal for the development of the worldwide bioeconomy (Patermann & Aguilar, 2018; Wohlgemuth et al., 2021).

15.3 Microbial Genomics

The genome of living organisms is composed of its complete genetic material that is generally DNA. In contrast, the genomes of RNA viruses are composed of RNA. The bioinformatic analyses of sequenced genomes of organisms allowed revealing genes involved in metabolism, adaptation, signaling, transport, and diverse molecular and cellular processes. In 1995, the first genome of a microbial cell, the bacterium *Haemophilus influenzae*, was sequenced (Fleischmann et al., 1995). The genome of the model bacterium *Escherichia coli* K-12 was sequenced in 1997 (Blattner et al., 1997). *E. coli* is the main organism used for genetic engineering. Automated DNA sequencing techniques have allowed sequencing of a huge number of microbial genomes. A variety of high-throughput tools have been developed for automated annotation, prediction, and visualization of genomes (Cumsille et al., 2023).

Metabolic reconstruction based on the analysis of the sequenced genomes has been carried out for various bacteria. The high metabolic versatility of specific microorganisms is attractive for biotechnological applications such as bioremediation of contaminated environments, promotion of plant growth, biocontrol of phytopathogens, the synthesis of biopolymers and bioactive compounds. The genome-guided metabolic reconstruction of different bacterial genera such as *Pseudomonas*, *Paraburkholderia, Acinetobacter, Halomonas,* and *Streptomyces* species has been crucial for the selection of bacterial strains with higher metabolic versatility and robust adaptive responses to environmental stresses for diverse biotechnological applications such as bioremediation and biotransformation (Seeger et al., 2003; Chain et al., 2006; Pieper & Seeger, 2008; Saavedra et al., 2010; Ponce et al., 2011; Perez-Pantoja et al., 2012; Durán et al., 2019; Macaya et al., 2019a, 2019b), plant growth promotion and biocontrol of phytopathogens (Canchignia et al., 2017; Vega-Celedón et al., 2021, 2024; Álvarez-Hubert et al., 2024; Larach et al., 2024; Castillo-Novales et al., 2025), synthesis of bioactive compounds (Undabarrena et al., 2016, 2017, 2021; Serna-Cardona et al., 2024), and production of bioplastics (Urtuvia et al., 2014, 2018; Álvarez-Santullano et al., 2021). *Pseudomonas* strains have been widely used for biodegradation of pollutants, plant growth promotion, and biocontrol of phytopathogens (Perez-Pantoja et al., 2012; Canchignia et al., 2017; Vega-Celedón et al., 2021, Larach et al., 2024). *Paraburkholderia* strains are relevant for biodegradation, biotransformation, plant growth promotion, and the synthesis of bioplastics (Seeger et al., 2003; Chain et al., 2006; Pieper & Seeger, 2008; Urtuvia et al., 2014, 2018; Álvarez-Santullano et al., 2021 Vega-Celedón et al 2021; Sepúlveda et al., 2025). *Halomonas* strains have been applied for the synthesis of bioplastics and bioactive compounds and plant growth promotion (Ma et al., 2020; Ye & Chen, 2021; Álvarez-Hubert et al., 2024). *Streptomyces* strains are the most relevant organisms for the synthesis of antibiotics (Undabarrena et al., 2016, 2017; Serna-Cardona et al., 2024). A genome-wide metabolic reconstruction revealed that *Paraburkholderia* species possess higher pathway redundancy of central carbon metabolism than *Burkholderia* species, which may confer robustness for their adaptation to harsh environments during bioremediation or plant growth promotion applications (Álvarez-Santullano et al., 2021). Additionally, genome mining predicts the synthetic capability of each microorganism, which is useful for the design and optimization of biorefinery schemes, reducing experimental time and costs. The simultaneous synthesis of PHB and ectoines by *Halomonas* species that were optimized through metabolic engineering is a remarkable example (Ma et al., 2020; Ye & Chen, 2021). In addition, the combination of genome-based approaches and experimental techniques allows the study of uncultured organisms and microbial communities, providing useful knowledge on microbial ecology for the conservation of ecosystems, management of bioprocesses, and health improvement (Fuentes et al., 2016; Zhou et al., 2022; Pittino et al., 2023; Gandolfi et al., 2024).

The application of genomics contributes to a deep understanding of (1) the variability of genetic components of microorganisms, their classification, and taxonomic identification, (2) predicting potential compounds with antimicrobial activity and novel chemical structures (Foulston, 2019), (3) the metabolism involved in biodegradation, (4) the adaptation of microorganisms to environmental stresses (e.g., salinity, extreme pH, extreme temperature) and contaminants (Plewniak et al., 2018;

Méndez et al., 2025), and (5) the impact of biotechnologies for environmental decontamination and sustainable agriculture on the native microbial community. Circular bioeconomy is based on biological resources derived from the biodiversity. Microbial genomics provides essential knowledge for the conservation of biodiversity and ecosystems through sustainable and efficient bioremediation and agriculture strategies (Buchmann-Duck & Beazley, 2020). Next-generation sequencing is useful for studying the structure, function, and composition of genomes of an entire community of microorganisms from diverse matrices, such as soil, water, sediments. Metagenomic applications in bioremediation include the generation of profiles of antibiotic resistance genes and other mobile genetic elements (Wang et al., 2013, 2014), dynamics of the structure of the microbial community during bioremediation processes of contaminated soils (Morgante et al., 2010; Ping et al., 2015; Fuentes et al., 2016) and the tracking of bacteria during decontamination processes (Morgante et al., 2010; Deng et al., 2016).

15.4 Bioremediation

Pollution and anthropogenic activities have adversely impacted >33% of arable soil, limiting agricultural productivity (Abhilash et al., 2016). The clean-up of polluted ecosystems is a major challenge for the 2030 United Nations (UN) Agenda for Sustainable Development, which should be addressed to promote the concept of "One Health" and UN SDGs such as SDG 6 (Clean water and sanitation), SDG 11 (Sustainable cities and communities), SDG 14 (Life below water), and SDG 15 (Life on land). Bioremediation technologies are useful for the clean-up of polluted ecosystems (Fuentes et al., 2014; Orellana et al., 2018, 2022; Macaya et al., 2019b). Main advantages of bioremediation include a natural process, the complete removal of pollutants, potential *in-situ* or *ex-situ* applications, and low carbon footprint (Fuentes et al., 2014; Macaya et al., 2019b; Orellana et al., 2022). The *ex-situ* technologies could be used *on-site* or *off-site* (Orellana et al., 2022). Decontaminated soils and water are crucial for sustainable cities, land and water, and diverse human activities such as urbanization, agriculture, fishery, aquaculture, sports, and tourism (FAO, 2018; Orellana et al., 2018, 2022). Therefore, the valorization of ecosystems after their clean-up via bioremediation and other treatments is also essential for a circular bioeconomy.

15.4.1 Environmental Contamination: Persist Pollutants and Their Removal by Microorganisms

The growth of food, transportation, and industrialization in society raises the use of chemicals and fossil fuels. Despite the growing development of new sustainable energy sources, the consumption of oil and its derivatives has not slowed down.

Their recalcitrance, toxicity, and continuous release into the environment convert these pollutants into a serious threat to human and ecosystem health (Shetty et al., 2023). The understanding of their behavior in the environment enables the development of more effective and sustainable bioremediation technologies (Bala et al., 2022). Major pollutants include petroleum-derived hydrocarbons, pesticides, heavy metals, industrial compounds such as polychlorobiphenyls (PCBs) and perfluoroalkyl and polyfluoroalkyl substances (PFAS), and microplastics, which will be described below.

Petroleum-derived hydrocarbons (HC) HC originate from animal and plant biomass that has been subjected to biogeological processes during millions of years (Liu et al., 2022). Petroleum is the main source of energy and materials for various industrial and daily activities, driving the global economy (Varjani & Upasani, 2016; Ahmed et al., 2020). Petroleum derivatives include diesel, gasoline, and jet fuel. Global oil demand in 2023 will be 102.97 million barrels per day, with 45% consumed by OECD countries (US Energy Information Administration, 2024). Petroleum consists mainly of aliphatic hydrocarbons (such as alkanes and alkenes), cycloalkanes (e.g., cyclohexane), monoaromatics (e.g., benzene, toluene, ethylbenzene, *o*-xylene, *m*-xylene and *p*-xylene, BTEX) and polycyclic aromatic hydrocarbons (PAHs) (e.g., anthracene), and trace amounts of heavy metals (Akmaz et al., 2011; Chaudhuri, 2010; Joshi et al., 2019). Due to anthropogenic activities, BTEX and PAHs, which are recalcitrant and carcinogenic, are widely distributed in the environment, representing a significant risk to human health (Fuentes et al., 2014; Sun et al., 2021). Heavy metals such as cadmium, chromium, lead, and mercury are common co-contaminants in hydrocarbon-impacted sites and represent a public health risk (Amezcua-Allieri et al., 2005; Tchounwou et al., 2012; Olaniran et al., 2013; Fuentes et al., 2014).

Pollution events negatively impact the environmental matrix (soil, water, or air), living organisms (plants, animals, microorganisms), and their ecological interactions. The structure, diversity, and abundance of microbial communities (bacteria, fungi, and archaea) are affected by pollution events (Macaya et al., 2019b). Proteobacteria and Bacilli are the main phyla in chronic oil-polluted sites. *Pseudomonas* and *Lactococcus* have been reported in oil wellheads, while *Prauseria* and *Bacillus* have been observed in storage tanks (Liu et al., 2019). *Alcanivorax*, *Marinobacter,* and *Oleispira* genera are strict hydrocarbon-clastic bacteria, which increase significantly in the sea after oil contamination (Yakimov et al., 2007). *Dietzia* sp. strains are capable of degrading short, medium, and long chain alkanes (Wang et al., 2011). Rare taxa, such as *Alkanindiges* that are not abundant in pristine soils, became dominant in the soil after diesel contamination (Fuentes et al., 2016). Hydrocarbon-clastic bacteria play a crucial role in the clean-up of hydrocarbon-impacted environments (Xu et al., 2018).

Pesticides The significant increase in the application of pesticides for food production, harvesting, and storage is associated with the food demand growth. The total pesticide use in the agricultural sector during 2022 was 3.7 million tons, rep-

resenting a 4% increase in consumption compared to the previous year (FAO, 2022a). Pesticides may be pure substances or mixtures, which are used by farmers to control microbes (fungicides), insects (insecticides), and weeds (herbicides). Although these compounds have specific targets, their action and wide use have impacted ecosystems and various forms of life including humans (Lin et al., 2016). Organochlorine insecticides (OC) are used to control pests such as malaria and typhus; however, they are legally banned in several countries. These compounds have been replaced by organophosphates (OP), such as carbamates and pyrethroids (Kumar et al., 2021a, 2021b). Synthetic s-triazine herbicides (atrazine, simazine) are applied to control weeds and grasses in crops. These herbicides alter plant growth and microbial communities, but are also major contaminants of terrestrial and aquatic ecosystems, threatening the sustainability of agricultural soils (Hernández et al., 2011). Diverse bacterial and fungal genera including *Arthrobacter, Aspergillus, Bacillus, Burkholderia, Nocardioides, Pseudomonas, Sphingobacterium, Sphingomonas,* and *Trichoderma* degrade different types of pesticides (Kumar et al., 2021a).

Polychlorobiphenyls (PCBs) PCBs are aromatic compounds containing chlorine atoms in different positions on two benzene rings, with more than 200 congeners. Their use became widespread toward the end of the 1920s. Their applications include dielectric materials in transformers and electrical capacitors, and additives in plastics and paints. PCBs are classified as persistent organic pollutants (POPs), which adsorb in soils and sediments, and bioaccumulate in various forms of life of impacted ecosystems (Seeger et al., 1995, 1997; Gomes et al., 2015). Due to their carcinogenic and immunogenic effects, their production was banned in the 1970s. However, PCBs are still in use in electrical equipment manufactured prior to the ban and are widely present in the environment (ATSDR, 2000; Palma et al., 2008; Dias-Ferrerira et al., 2016).

The degradation of PCBs is mediated by bacteria under both aerobic and anaerobic conditions. *Paraburkholderia*, *Pseudomonas*, *Comamonas*, *Cupriavidus*, *Sphingomonas*, *Acidovorax*, *Rhodococcus*, and *Bacillus* strains are capable of degrading PCBs (Pieper & Seeger, 2008). *Desulfitobacterium*, *Desulfomonile*, and *Desulfuromonas* are capable of dehalogenating chlorinated aromatic compounds (de Weerd & Suflita, 1990; Sanford et al., 1996; Krumholz, 1997). *Paraburkholderia xenovorans* LB400 is the model aromatic-degrader that degrades an unusually wide range of aromatic compounds including PCBs and possesses robust adaptation mechanisms to diverse stresses (Seeger et al., 1999; Chain et al., 2006; Rodriguez-Castro et al., 2024; Méndez et al., 2025).

Heavy metals (HM) HM can be defined as a group of metals (and metalloids) that may be toxic to various forms of life even at low concentrations. This classification includes cadmium, mercury, copper, arsenic, lead, chromium, nickel, and zinc. Due to the development of intensive agriculture and other industrial activities, HM pollution has emerged as a serious threat to the environment, particularly to soil (Sarwar et al., 2016). This type of contamination is persistent and irreversible, impacting not

only terrestrial and aquatic environments but also affecting human health by bioaccumulating in the food chain, causing harmful effects such as skin cancer, brain damage, cardiovascular and respiratory disorders, and infertility (Kankia & Abdulhamid, 2014; Ayangbenro & Babalola, 2017; Alviz-Gazitúa et al., 2019). More than 5 million sites contaminated with heavy metals or metalloids have been reported, affecting over 500 million hectares of soil (Liu et al., 2018). The global economic impact of this contamination is estimated to exceed USD10 billion per year (He et al., 2015). The primary source of HM in soils comes from the Earth's crust, where natural geological processes release elements such as Pb, Cu, Zn, Mn, and Cd into the soil (Muradoglu et al., 2015; Sarwar et al., 2016). Anthropogenic sources include industrial processes and traffic. HM accumulate in roadside soils and even in agricultural soils near roads (Nabuloa et al., 2006). Impacted crops may absorb HM through their roots, which could reach the stems and leaves (Prasad & Freitas, 2000).

Chromium is widely used in various industries; hexavalent chromium Cr(VI) is the most toxic and mutagenic form. Endophytic bacteria such as *Bacillus* sp. L14 remove cadmium from contaminated soils, accumulating this HM in their cytoplasm (Luo et al., 2011). Soluble Cr(VI) reductases have been described in *Pseudomonas putida* (ChrR), transforming Cr(VI) into Cr(IV). The YieF protein reduces Cr(VI) to Cr(III) in *Escherichia coli* (Cheung & Gu, 2007). Soluble Cr(VI) reductases have been described in *Pseudomonas putida* (ChrR), which transforms Cr(VI) to Cr(IV). *Cupriavidus metallidurans* and other species of the genus *Pseudomonas*, such as *Ps. stutzeri,* reduce Hg(II) to Hg(0) (Rojas et al., 2011; Purkan et al., 2016; Bravo et al., 2020).

Emergent contaminants Emergent contaminants have been determined in soil, but primarily in aqueous environments such as aquifers, oceans, and water sources (Zahn et al., 2020). The quantification of these pollutants in low levels is an important challenge (Zahn et al., 2020). Main emergent pollutants compounds are perfluoroalkyl and polyfluoroalkyl substances (PFAS) and microplastics (MP). Although PFAS are typically present in low concentrations, higher levels (mg/L) have been observed in water bodies impacted by firefighting activities or near fluorochemical manufacturing industries, negatively affecting the environment and human health (Vedajiri et al., 2018). Microbial bioremediation has not been applied yet, mainly due to their recalcitrance, the toxicity of their intermediates, and the unavailability of degrading microorganisms (LaFond et al., 2023).

MP are defined as plastic particles smaller than 5 mm, which are of increasing environmental concern. The presence of microplastics (MP) has been reported in marine and terrestrial ecosystems. The most common forms of MP include fibers and pellets. Their presence in soils and water represents a significant risk to human health and the environment. The main strategies for managing MP include pyrolysis, chemical degradation, biological degradation, and the development of biodegradable alternatives, such as bioplastics (Chia et al., 2021) (further description in Sect. 15.6). Various strategies have been proposed to clean up MP-containing

matrices. MP extraction using filters or pumps, followed by chemical or biological degradation, can be effective. However, scalability is still a limitation (Wong et al., 2020). Due to the occurrence and distribution of MP within matrices it is important to develop remediation strategies (Fu et al., 2020). Analytical tools are crucial to quantify MP release, particularly in areas with unregulated industrial and/or domestic waste management (Bilal & Iqbal, 2020).

These compounds and elements are associated with the expansion of industrialization, urbanization, and socioeconomic growth. Despite this development, the persistent use of these compounds gradually impacts the environment. Urban ecosystems, forests, wetlands, and agricultural soils play a crucial role in urban health by providing multiple benefits to the surrounding biota; contamination directly impacts the microbiota and health of ecosystems, affecting their tangible (e.g., food, water) and intangible (e.g., nutrient cycles, temperature regulation, bioremediation) ecosystem services.

Despite the high toxicity to the microbial communities of pollution events caused by HC, pesticides, HM, and PCBs, specific microorganisms have pollutant-removing capabilities. In pristine ecosystems, hydrocarbonoclastic bacterial genera are present at low levels, representing less than 0.1% of the total community (Fuentes et al., 2016; Rodríguez-Castro et al., 2022). After an oil spill, the abundance of HC-degrading bacteria increases significantly up to 60% of the microbial community (Fuentes et al., 2016). Studies on *s*-triazines bioremediation showed that the application of organic amendments alters the structure of the microbial community, favoring microorganisms capable of degrading *s*-triazines (atrazine, simazine) and using these substrates as nitrogen sources, such as Proteobacteria (e.g., *Pseudomonas*) and Planctomycetes (Martin-Laurent et al., 2004; Rhine et al., 2003; Hernández et al., 2008; Morgante et al., 2010). Supplementation with PHA in marine sediments contaminated with PCBs increases degrading microorganisms, but reduces the microbial community diversity (Botti et al., 2023). Agricultural soils chronically exposed to heavy metals such as copper contain adapted bacterial communities including copper-resistant strains from *Sphingomonas*, *Stenotrophomonas,* and *Arthrobacter* genera with genetic determinants that confer resistance to copper and other heavy metals (Altimira et al., 2012).

15.4.2 Bioremediation: Strategies and Innovation

Microorganisms with enhanced pollutant-removing capabilities and high resistance to environmental stresses (e.g., salinity, pH changes) are selected in polluted sites. The metabolic capabilities of the microbiota of the impacted ecosystems are crucial for bioremediation. Bioremediation is an increasingly applied technology, due to its low cost, biological basis, and environmentally friendly nature (Navia & Seeger, 2006; Fuentes et al., 2014; Macaya et al., 2019b). A high number of contaminated sites require technologies for their decontamination. To date, China has more than 2 million polluted sites, the USA has >500,000

impacted sites, Europe >340,000 sites, and Chile >10,000 contaminated ecosystems including 600 urban sites (State Council of China, 2013; Zvomuya & Murata, 2013; Van Liederkeke et al., 2014). The industry associated with bioremediation processes represents a global market of USD186.3 billion in 2023, with a projected Compound Annual Growth Rate (CAGR) of 9.9% by 2030 (BCCResearch, 2024; Orellana et al., 2022).

Currently, there are various strategies for decontaminating impacted ecosystems. Physical remediation (PR) involves actions to extract the contaminated matrix (e.g., soil, water) through excavation, pumping, or air injection (Fuentes et al., 2014). Chemical remediation (CR) uses chemical agents to transform contaminants into less toxic compounds (Koul et al., 2018). Natural attenuation (NA) is a spontaneous natural process (biological, chemical, and physical) under monitoring to decontaminate the matrix (Pradhan et al., 2021). Bioremediation (or biological remediation) employs the metabolic capabilities of microorganisms (native or exogenous) to degrade contaminants. Compared to PR and CR, bioremediation produces less toxic intermediates. Compared to NA that occurs exclusively under natural conditions, bioremediation accelerates decontamination (Pradhan et al., 2021).

Different bioremediation strategies are used for the clean-up of polluted ecosystems. Biostimulation is a technology wherein nutrients (e.g., nitrogen, phosphorus) or biologically derived surfactants are added to promote the degradation by the indigenous microbiota of the contaminated environment. In bioaugmentation, indigenous or non-indigenous pollutant-degrading microorganisms are introduced to increase the degradation rate of contaminants (Ron, 2000; Navia & Seeger, 2006; Morgante et al., 2010; Fuentes et al., 2014). In bioventing, the contaminated environment is aerated to provide electron acceptor oxygen to stimulate microbial metabolism (Fuentes et al., 2014). The selection of an appropriate bioremediation strategy should be based on the physicochemical properties of the impacted matrix and the pollutants (Fig. 15.2). The bioremediation process may operate *in situ* or *ex situ*. Particularly, for *ex-situ* processes, two variants are: 1) *off-site*, where the contaminated matrix is transported to an external facility, outside the site, and 2) *on-site*, where the contaminated material is removed but treated at the original location (Hernández et al., 2008; Macaya et al., 2019b; Bravo et al., 2020).

Associated with major sustainable development challenges, such as the sustainable management of natural resources and the balance of social evolution, current biotechnologies should be innovative, enabling the production of biomasses (e.g., degrading microbial consortia, production of biostimulants, antioxidants) for sustainable environmental decontamination services (Fuentes et al., 2014). The bioeconomy offers interesting guidelines by promoting improvements in sustainable industrial production, reducing environmental impact, and fostering the safe preservation of the environment (Fig. 15.3) (The European Plant Science Organisation, 2011; Fuentes et al., 2014; Labuto & Carrilho, 2016).

Depending on the type of contamination and the physicochemical characteristics of the impacted matrix, one or more complementary bioremediation strategies

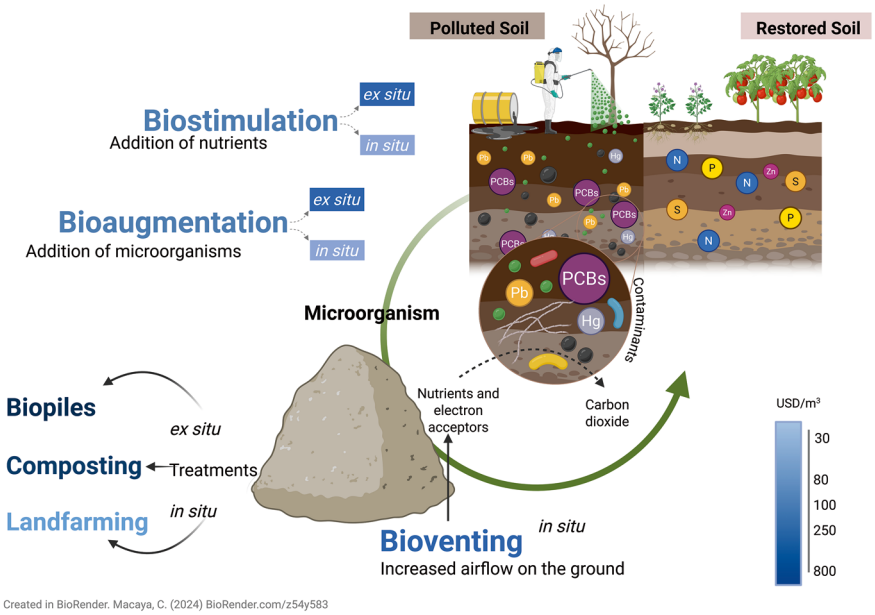

Fig. 15.2 Biological decontamination technologies. Graphical representation of the bioremediation strategies: biostimulation, bioaugmentation, bioventing (in which the contaminated environment is aerated to supply oxygen for microbial activity), biopiles, composting, and landfarming. The blue scale range represents the economic cost (in US$/m^2) of each technology, with the lowest cost described in light blue, and the most expensive in dark blue. Adapted from Ester G. Rivera, 2023. Master thesis in Environmental Biochemistry. University of Chile

can be applied. For decontamination, a critical factor is the bioavailability of contaminants, especially in aquatic environments. Microbial biosurfactants enhance the mobility of hydrophobic pollutants, increasing their bioavailability (Singh et al., 2007; Ke et al., 2018; Astuti et al., 2019). Biostimulation with biosurfactants (e.g., saponins) has been successfully used in the decontamination of HC and HM (Kaczorek et al., 2008; Lord, 2010; Kiliç et al., 2011). In accordance with the principles of the circular bioeconomy, the use of local agricultural waste/by-product to alleviate the metabolic stress of pollutant-degrading bacteria contributes to closing the cycle of each by-product. Berry extract has been used as a source of antioxidants in the decontamination of coastal soils contaminated with HC (Ponce et al., 2011).

Biostimulation with the addition of nutrients has been widely used (Macaya et al., 2019b). Feathers are one of the main wastes of the poultry industry, with an estimated global production of 8.5 billion tons (Holkar et al., 2018). *Streptomyces* sp. G11C synthesizes keratinases that degrade feathers, generating a medium rich in proteins, nitrogen, and essential amino acids, which can be used to stimulate native microbiota activity for soil restoration (Habbeche et al., 2014; Holkar et al., 2018; González et al., 2020; Jagadeesan et al., 2023).

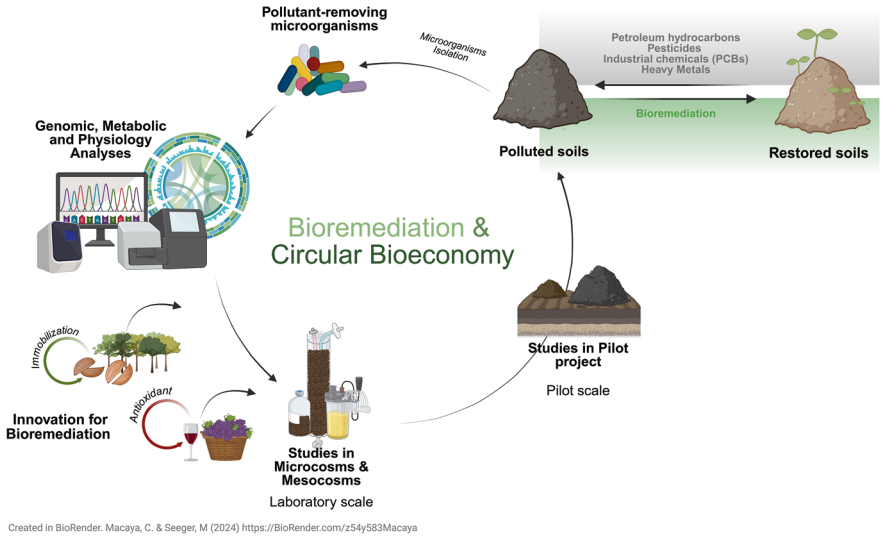

Fig. 15.3 Bioremediation processes and circular bioeconomy. Graphical representation of the processes of isolation of soil microorganisms with metabolic capabilities for the removal of pollutants (petroleum hydrocarbons, pesticides, industrial chemicals such as PCBs, and heavy metals), their genomic and functional characterization, innovation processes in bioremediation strategies related to the valorization of agricultural wastes, decontamination studies at laboratory and pilot scales, and the clean-up of impacted soils toward soil restoration

Several factors influence the successful application of a bioaugmentation strategy, including fluctuations in environmental parameters (temperature, salinity, and pH), moisture retention, and contaminant concentration. Regarding implementation costs, these are not significant if existing infrastructure is already in place for maintaining moisture and injecting reducing agents, as these same systems can be used for strain inoculation. While the use of such facilities facilitates the distribution of the inoculum within the matrix, applying it in an aqueous solution poses the risk of washing out and predation of the inoculated microbes (Boon & Verstraete, 2010). Immobilization is useful to improve the survival and stability of pollutant-degrading bacteria, extending the lifespan of bioremediation agents by facilitating cell reuse, reducing costs of re-inoculation, and promoting cell recycling processes. In line with the concept of waste valorization, matrices derived from agro-industrial residues have gained considerable interest in bioremediation processes (Bayat et al., 2015). Studies on contaminated soils and aquifers demonstrate that bioaugmentation is an eco-friendly, effective, and affordable clean-up treatment. Bioaugmentation with *Pseudomonas* sp. strains ADP1 and MHP41 in s-triazine-contaminated soils achieved >80% contaminant removal (Lima et al., 2009; Hernández et al., 2008; Morgante et al., 2010). Bioaugmentation with nitrogen removal bacteria in wastewater enhances aerobic nutrient removal (Chen et al., 2015). In these studies, bioaugmentation significantly changes the microbial community structure.

15.5 Agricultural Bioproducts

Climate change has a significant negative impact on agriculture, ecosystems, and health. Agriculture is affected by climate change, which causes drought, flooding, and the increase of extreme temperatures in diverse regions (Raza et al., 2019). Therefore, climate change increases plant abiotic and biotic stress, and favors emerging phytopathogens (Valenzuela et al., 2018; Besoain et al., 2019; Alfaro et al., 2023; Larach et al., 2024). Microorganisms and plant natural products are useful to promote plant growth and to protect plants from biotic and abiotic stresses (Olivera et al., 2021; Vega-Celedón et al., 2021, 2024; Álvarez-Hubert et al., 2024; Montenegro et al., 2024).

Agriculture faces increasingly complex challenges due to population growth and the depletion of natural resources. The world population is projected to increase to over 10 billion people in the next 30 years. Therefore, the food supply must increase by 60% to cope with the projected demand in 2050 (United Nations, 2015). In view of this, the global demand for the use of pesticides and fertilizers has increased (FAO, 2022a). The misuse of pesticides and fertilizers contributed to the desertification of agricultural lands, the loss of biodiversity in ecosystems, especially in microhabitats (Sporen et al., 2024) and the decrease in crop productivity and increase in physiological disorders in humans (Bedair et al., 2022). International regulations such as EU 2015/408 establish the replacement of traditional chemical agents used in agriculture with sustainable alternative methods with similar effectiveness in the control of agricultural diseases (Delgado et al., 2021). The European Union aims to reduce pesticide use by 50% by 2030 (Salerno et al., 2024). This context has driven the search for more sustainable alternatives, such as bioproducts, that are central to transforming agriculture toward more sustainable practices (FAO, 2022a). Bioproducts not only reduce dependence on chemical inputs but also promote the efficient use of natural resources such as soil and water, which contributes to the resilience of agricultural systems against the effects of climate change.

Globally, the increasing demand for organic food and the interest in more human and environmentally responsible agriculture drive significant growth in the bio-based products market. The global agricultural bio-based products market size was estimated at US$9.9 billion in 2023 and is expected to grow at a CAGR of 7.2% from 2024 to 2030. Rising demand for organically cultivated food products is projected to be a key driving factor for the market (Agricultural biologicals market size, share and growth 2030). Organic farming focuses on minimizing or eliminating the use of synthetic mineral fertilizers, chemical protection agents, plant growth regulators, and genetically modified organisms. This issue reflects a trend toward agricultural practices that prioritize sustainability to meet the growing food demands and ensure that this food is produced ethically, safely, and with minimal environmental impact (FAO, 2022b).

Organic agriculture management aims to maximize the use of bioproducts in agricultural production (Aipova et al., 2019). This shift toward sustainable agriculture aims not only to increase productivity and improve the health of ecosystems but also to ensure that future food is safe, nutritious, and produced responsibly.

International policies, such as the UN 2030 Agenda for Sustainable Development, reinforce these commitments to sustainable agriculture, driving the transition toward an economic model that reconciles growth with care for the environment (Matera et al., 2024).

15.5.1 Definition and Classification of Agricultural Bioproducts

Agricultural bioproducts are materials from living organisms or their components that are used to improve agricultural productivity, soil health, and crop protection from pests and diseases. Figure 15.4 shows the classification of different

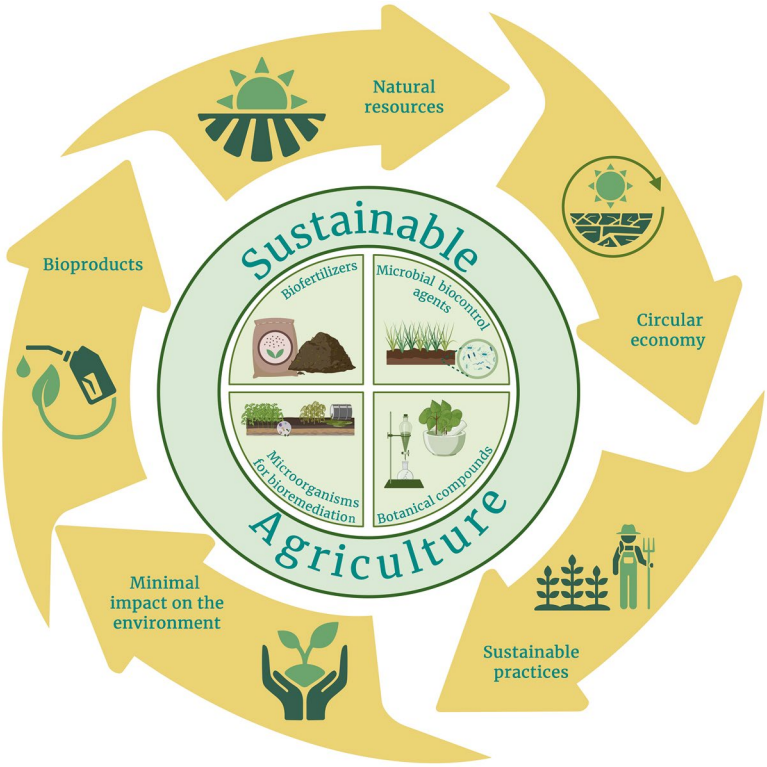

Fig. 15.4 Classification of bioproducts for agriculture in the context of circular bioeconomy. Graphical representation highlights the role of bioproducts—biofertilizers, microbial biocontrol agents, microorganisms for bioremediation, and botanical compounds—in sustainable agriculture. Their connection to natural resources, sustainable practices, minimal environmental impact, and the circular economy are indicated

bioproducts described: (1) biofertilizers, (2) microbial biocontrol agents, (3) botanical compounds, and (4) microorganisms for the bioremediation of polluted agricultural soils (described in the Sect. 15.4–Bioremediation).

Biofertilizers Biofertilizers contain living microorganisms, and their application to the seed, plant surface, or rhizosphere increases the supply of mineral element concentrations to crops, thus promoting growth (Demir et al., 2023). Biofertilizers are alternative fertilizers that increase plant growth and yield and play a multifunctional role in soil and plants. Plant growth-promoting microorganisms (PGPMs) have emerged as a sustainable alternative to conventional chemical fertilizers, a potentially advantageous technique for improving crop productivity, quality, and food security (Lopes et al., 2021; Kumar et al., 2021a). PGPMs act as biofertilizers (Lopes et al., 2021) and include plant growth-promoting bacteria (PGPB) and arbuscular mycorrhizal fungi (AMF) that increase biomass production in plants by synthesizing phytohormones, fixing nitrogen, solubilizing phosphate and potassium, and increasing plant resistance to pathogens and environmental stresses (Ma, 2019; Aloo et al., 2022; Bhardwaj et al., 2014; Velásquez et al., 2020a, 2020b; Kumar et al., 2021a; Vega-Celedón et al., 2021). PGPB and AMF can improve root health in plants by increasing stress tolerance and growth, optimizing nutrient uptake and nutrition through the production of secondary metabolites and increasing disease resistance (Velázquez et al., 2020b; Rillig & Mummey, 2006; Adesemoye & Kloepper, 2009; Vejan et al., 2016; de Andrade et al., 2023). PGPMs promote healthy plant growth and are crucial in reducing greenhouse gas emissions and water pollution, supporting global sustainability goals (Costa et al., 2019).

Abiotic stresses, including cold, heat, drought, and salinity, significantly impact crop production and quality; more than >50% of global yield losses are attributed to abiotic stresses (Wang et al., 2016). Climate change further exacerbates these challenges, with higher exposure of plants to extreme temperature events such as frost. Psychrotolerant PGPB may protect and promote plant growth under low-temperature conditions (Vega-Celedón et al., 2021).
PGPB and AMF form beneficial associations with plants, promoting growth, nutrient availability, and protection against pathogens. PGPB and AMF solubilize nutrients, such as phosphate and potassium, increasing their availability to plants. *Pseudomonas fluorescens* is known for its phosphate-solubilizing capabilities, while *Azospirillum brasilense* enhances nitrogen fixation, crucial for crop productivity (Lugtenberg & Kamilova, 2009; Hashem et al., 2019). Diverse bacteria also produce phytohormones such as auxins, gibberellins, and cytokinins, which directly promote plant growth and improve root architecture, facilitating access to soil nutrients (Gamez et al., 2019; Molloy et al., 2013; Vega-Celedón et al., 2021, 2024). AMF, such as *Funneliformis mosseae*, establish mutualistic relationships with plant roots by forming specialized structures like arbuscules within the root cortex. These fungi improve water and nutrient uptake, particularly phosphorus, and offer plants enhanced resistance to abiotic stresses such as drought and salinity (Argaw & Akuma, 2015; Velásquez et al., 2020a). Additionally, AMF may induce systemic

resistance in plants, stimulating the plant's immune system and conferring more resistance to pathogens (Velásquez et al., 2020b).
Both PGPB and AMF contribute to pathogen suppression through direct and indirect mechanisms. Direct methods include the production of antimicrobial compounds (e.g., lipopeptides by *Bacillus subtilis*) and enzymes (e.g., lipases and proteases by *Pseudomonas veronii*), which inhibit plant pathogens (Ongena & Jacques, 2008; Canchignia et al., 2017). Indirectly, these microorganisms may outcompete pathogens for resources and niches within the rhizosphere, decreasing pathogen proliferation (Solis-Ramos et al., 2023).

Microbial biocontrol agents The use of microbial biocontrol agents in agricultural diseases and insect pests is of increasing importance due to their effectiveness in the control of pathogens and in extending the shelf-life of post-harvest products (Carmona-Hernández et al., 2019). Despite challenges such as production costs and regulation, the demand for biopesticides is expected to increase significantly in the coming years, driven by policies that favor more sustainable agricultural practices. This approach reinforces the interrelationship between agricultural productivity and environmental conservation, positioning biopesticides as a key component in the development of sustainable agricultural bioproducts (Šunjka & Mechora, 2022).

Generally, bacteria, fungi, and yeasts are used as microbial biocontrol agents of plant pathogens (Delgado et al., 2021; Olivera et al., 2021; Salerno et al., 2024), reducing the environmental impact and risks to human health (Santos et al., 2020). Biocontrol agents (BCAs) provide an effective and less harmful alternative to conventional chemical pesticides. Their mode of action includes competition for nutrients and space, production of antimicrobial compounds, induction of host defense responses, and parasitism (Romero et al., 2022; Olivera et al., 2021; Santos et al., 2020). A key advantage of BCAs is their specificity toward target pests, which minimizes damage to non-target organisms and contributes to biodiversity in agricultural ecosystems. Furthermore, their application promotes regenerative agriculture practices, which support soil health and crop resilience to climate change (Szewczuk-Karpisz et al., 2022). Climate change also alters disease pressure caused by known and emerging pathogens (Singh et al., 2023a). Because of the latter it is interesting to note the impact of temperatures on the development of microorganisms, and to evaluate their biocontrol efficacy at different temperatures (Larach et al., 2023; Castillo-Novales et al., 2025). Several bacteria used as BCAs in plant diseases are *Gluconobacter cerinus*, *Bacillus subtilis*, *B. amyloliquefaciens*, *B. licheniformis*, and *Paenibacillus pasadenensis* (Olivera et al., 2021; Romero et al., 2022; Matera et al., 2024). *Trichoderma* spp. and *Bacillus* spp. have been widely used for the biological control of plant diseases caused by soil phytopathogens, mainly against *Phytophthora*, *Rhizoctonia*, *Sclerotium*, *Pythium*, and *Fusarium* (Chet & Inbar, 1994; Ahmed et al., 2000, 2003; Ezziyyani et al., 2004). Yeasts reported as BCAs include *Candida oleophila, Metschnikowia fructicola*, *M. pulcherrima, Cryptococcus albidus*, *Hanseniaspora uvarum*, *H. osmophila,* and *Lachancea thermotolerans* (Olivera et al., 2021; Romero et al., 2022; Salerno et al., 2024). Microbial consortia

may increase the BCA's efficiency due to the exploitation of their complementary and synergistic characteristics (Vega-Celedón et al., 2021). An example is a bioproduct composed of a bacterium and a yeast (*Gluconobacter cerinus* and *Hanseniaspora osmophila*) that has been reported and patented (WO2017088081A1), and is used to control gray rot and summer bunch rot in post-harvest table grapes with synergic effects (Delgado et al., 2021; Olivera et al., 2021).
In the case of insect-caused pests, BCAs act as bioinsecticides. *Bacillus thuringiensis* (Bt) is a bacterium that produces toxic proteins for various insect pests and is widely used in agriculture to control these insects without harming natural predators (Lacey & Shapiro-Ilan, 2008; Santos et al., 2020). *Beauveria bassiana* is an entomopathogenic fungus that infects and kills insect pests, and is effective in the control of a wide range of insects (Zimmermann, 2007; Cappa et al., 2024).

Botanical compounds These compounds have long been recognized for their potential as eco-friendly alternatives to synthetic pesticides in agricultural pest management, offering a sustainable approach to addressing these challenges (Zhang et al., 2024; Gupta et al., 2024). Diverse compounds may have effects on multiple pests caused by fungi, bacteria, and insects (Montenegro et al., 2013, 2018a, 2018b). For example, essential oils from plants such as *Cupressus sempervirens* and *Litsea cubeba* have significant insecticidal properties against pests such as *Sitophilus oryzae* and *Drosophila suzukii* (Gao et al., 2024). The essential oil extracted from *Poiretia latifolia* flowers exhibits strong antifungal activity against pathogens such as *Monilinia fructicola* and *Monilinia laxa*, which are known to cause severe damage to fruit crops (Madrid et al., 2024). These examples underscore the potential of botanical compounds to target a wide range of pests while minimizing the ecological footprint of agricultural practices.

A polygodial terpene-type drimanic compound from *Drimys winteri* shows antifungal activities against the phytopathogens *Aspergillus flavus* and *Fusarium oxysporum* (Montenegro et al., 2024). In addition, this compound blocks the chemosensory receptors in insects, showing a potential application for insect pest control (Zapata & Smagghe, 2010; Prota et al., 2014; Inocente et al., 2019; Anese et al., 2018; Paz et al., 2018; Montenegro et al., 2013; Opiyo, 2021).
Due to their low aqueous solubility and stability, diverse natural compounds have limited use in delivery systems. Nanotechnological methods may be useful to overcome these limitations for agrochemicals (Aravena et al., 2021; Manjesh et al., 2022). Plant extracts of *Psoralea* used in nanoemulsions reduce the viability of the fungus *Fusarium oxysporum* and control fusariosis in tomatoes (Aravena et al., 2021). Plant extracts of *Manilkara subsericea*, *Acorus calamus*, *Allium sativum*, *Copaifera duckei*, *Ricinus communis*, and *Nicotiana tabacum* have been used in nanoemulsions against the insects *Dysdercus peruvianus*, *Sitophilus oryzae*, *Spodoptera littoralis*, *Aedes aegypti*, and *Anopheles culicifacies* (Sharma et al., 2020; Giuliano et al., 2024). Nanoparticles based on crustacean chitin exoskeleton (chitosan) have also been used for Gram-positive and Gram-negative bacterial control (Kumar et al., 2020). Recently, active coatings based on oxidized chitin

nanocrystals combined with silk fibroins have been applied for the control of *Colletotrichum gloeosporioides* in avocado (Ferreira et al., 2023).

15.5.2 Future Projections

Biofertilizers, BCAs, and botanical compounds are sustainable alternatives to chemical fertilizers and pesticides. These products help to reduce soil and water pollution. The growing demand for these bioproducts reflects increased concern for the environment and higher regulations on the use of synthetic chemicals. By improving soil health, promoting microbial biodiversity, and improving nutrient cycles, these bioproducts favor a more resilient agriculture. These bioproducts will be key to fulfilling the challenges of climate change and the pressure on the natural resources. This will improve global food safety, but also lead to an adaptation of regulations and public policies to ensure their safety and efficacy.

Nanotechnology in agriculture is an emerging field with the potential to revolutionize crop production through improved disease resistance, nutrient use, and crop yield and to contribute to the development of less toxic biopesticides with increased stability and enhanced activity on target pests (Bharani et al., 2014; Wang et al., 2016). The integration of Artificial Intelligence (AI) offers promising opportunities to optimize the application of these bioproducts. By analyzing variables such as temperatures, pH, and electrical conductivity, AI can enable precise and timely utilization, maximizing the effectiveness of bioproducts and paving the way for smarter, more sustainable agricultural practices. AI has been already applied to detect plant illness caused by specific pathogens in tomato plants (Vasconez et al., 2024).

The future of agriculture is intrinsically linked to the adoption of bio-based products, requiring a multi-faceted approach. Government support in the form of financial incentives, subsidies, and research funding is essential to promote the development, testing, and adoption of these products, alongside policies that encourage their use in agricultural practices. Collaboration among researchers, farmers, and industry stakeholders is crucial to incorporate bio-based products into the market, develop effective application methods, and ensure their successful integration into agricultural systems. Consumer awareness also plays a pivotal role; educating consumers about the benefits and importance of organic products is critical to driving demand and supporting the transition to a sustainable food system. This organic revolution is not merely a trend but a necessary step toward establishing a healthier, more resilient, and sustainable food system that benefits both people and the planet.

15.6 Bioplastics and Natural Bioproducts

Novel biomaterials and antibiotics are demanded by medicine for the treatment of diverse diseases and for tissue engineering (Undabarrena et al., 2017; Vilchez et al., 2021). Bio-based, biodegradable bioplastics may replace fossil-based plastics, wherein polyhydroxyalkanoate (PHA) is an attractive alternative for biorefining from bacterial biomass (Urtuvia et al., 2014; Álvarez-Santullano et al., 2021; Rosenboom et al., 2022). These biodegradable and biocompatible polyesters have been applied as added-value biomaterials for tissue (skin) engineering and drug delivery (Sanhueza et al., 2020; Vilchez et al., 2021; Sepúlveda et al., 2025). The increasing antimicrobial resistance (AMR) of human pathogens, coupled with emerging human and animal pathogens, which are favored by climate change and rising temperature, requires novel antibiotics (Undabarrena et al., 2016, 2017, 2021). Microorganisms and plants are key players in antibiotic synthesis and discovery.

The production and use of plastics in modern life have become essential for our daily activities. Fossil-based plastics impact the environment through gaseous contaminants, including CO_2, nitrogen oxides, and dioxins (Walker & Rothman, 2020). The distribution of macroplastics, microplastics and nanoplastics in natural environments may affect human health, biodiversity, ecological systems and landscapes (Ali et al., 2023; Bai et al., 2021; Kumar et al., 2023; Zhao et al., 2024).

Each year, around 415 million tons of fossil-based plastics are produced. Nearly 65% of the plastics is eventually disposed of in landfills or subjected to incineration, which represents around 86% of total plastic waste (5400 million tons), while the other 14% is recycled (Ali et al., 2023). Bio-based plastics are produced from biomass such as sugars, lignin, and vegetable oils, and other renewable raw materials. Like fossil-based plastics, they can be classified as biodegradable or non-biodegradable (Fig. 15.5) according to their capability to be biologically decomposed in the environment by microorganisms, into water, CO_2, CH_4, and biomass. The International Standardization Organization established bioplastic biodegradability with 90% of mass converted into CO_2 or CH_4 in a time span of 60–180 days in different environments and treatment systems according to ISO 14855, ISO 20200, ISO 16929, ISO 17556, ISO 16221, ISO 15985, ISO 11734, ISO 14853 (Folino et al., 2023).

15.6.1 Classification and Properties of Bioplastics

Bioplastics include: 1) bio-based non-biodegradable; 2) bio-based biodegradable; 3) petrochemical-based biodegradable. They are considered particularly well-suited as part of a circular bioeconomy due to various aspects depending on their origin and biodegradability:

1. *Bio-based non-biodegradable.* These types of plastic are synthesized from renewable biological mass, reducing the use of non-renewable petrochemical resources contributing to the decarbonization of the economy. Using waste biomass as raw material reduces the environmental impact associated with landfill disposal or agricultural incineration, promoting circular schemes. Nevertheless, at the end of their lifecycle they are introduced into the right cycle (Fig. 15.5) to end up in mechanical recycling or landfill.
2. *Bio-based biodegradable.* The capability to be biodegraded reduces waste generation at the end of their lifecycle. Biodegradation allows organic recycling of carbon mass to produce raw material of photosynthetic origin or energy, to be integrated in the polymer manufacture line or associated industries (Rosenboom et al., 2022). A comprehensive waste management infrastructure that efficiently collects and processes bioplastics is essential to ensure an effective integration into a circular bioeconomic system (Khodaei et al., 2021; Kuenneth et al., 2022; Mukherjee & Koller, 2023).
3. *Petrochemical-based biodegradable.* Despite their origin, they are considered bioplastics due to their capacity to be decomposed by living organisms. Therefore, at the end of their lifecycle, the main and basic chemical compounds are restored to the environment and used as raw material in the living cycle (Fig. 15.5). Otherwise, specific petrochemical-based biodegradable plastics can be chemically recycled at the building block level through depolymerization techniques such as pyrolysis or solvolysis (Fredi & Dorigato, 2021).

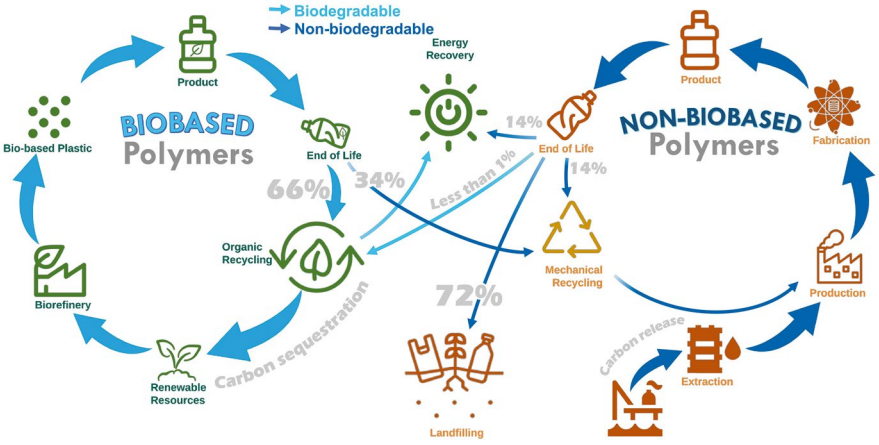

Fig. 15.5 Bio-based and non-biobased polymers cycles and their disposal at the end of their life-cycle. The life cycle of bio-based and non-biobased polymers shows that up to 66% of bio-based polymers are recycled, whereas 72% of non-biobased polymers are disposed in landfills. Thirty four percent of bio-based polymers are channeled into non-biobased polymers, highlighting future challenges in plastic life-cycle. Arrows indicate the flow and percentage of each process. Light and dark blue arrows indicate biodegradable and non-biodegradable paths, respectively. Percentages are reported by Ali et al. (2023).

Polymers extracted from biomass This group includes polysaccharides and proteins; macromolecules synthesized in/by living organisms with specific energetic or structural functions. The most useful polymers used in bioplastics production and research are starch, chitosan, gelatin cellulose, lignin, and zein. Starch is a polysaccharide that is recovered from agricultural waste such as banana and potato peel (Kiran et al., 2022; Imoisili & Jen, 2023), woody sources such as oil palm trunk (Hernando et al., 2024), edible resources such as corn (Rajesh et al., 2024) or cassava (Yang et al., 2023); and microalgae (Six et al., 2024). Chitin, which is mainly produced from the exoskeletons of crustaceans such as shrimp or crab, fungi, or insects, has been used for chitosan bioplastic production that is useful for food preservation (Kiran et al., 2022; Zhao et al., 2023), and for biomedical and pharmaceutical applications (Hisham et al., 2024; Kedir et al., 2022). Gelatin is mainly obtained from collagen from connective tissue, skin, and animal bones. This biopolymer has been widely used in the production of gels, microparticles, and films for pharmaceutical and biomedical applications (Amelia et al., 2024; Hui-Zhong et al., 2023), while novel functional bioplastic applications such as edible film packaging (Ratna et al., 2023). Lignocellulose is comprised of cellulose and lignin, which may be extracted alone or in combination to obtain bioplastics for food packaging and single-use bioplastic applications (Rosenboom et al., 2022). Zein is a particular protein that represents nearly 50% of the total protein in corn and can be obtained from corn dry-milling or wet-milling, which may be used in drug delivery, food packaging, or tissue engineering (Jaski et al., 2022; Yuan et al., 2022; Lan et al., 2023).

Polymers produced by microorganisms Diverse microorganisms produce biopolymers as carbon and energy storage. Polyhydroxyalkanoates (PHAs) are a group of linear aliphatic polyesters with different monomeric compositions that influence the physical properties of the final bioplastic. More than 150 types of hydroxyalkanoate monomers have been described, depicting the versatility of these polymers for a wide range of applications (Rehm, 2003). Polyhydroxybutyrate (PHB) is the most abundant PHA produced by different bacteria including *Pseudomonas*, *Bacillus*, *Cupriavidus*, *Paraburkholderia,* and *Burkholderia (Sepúlveda et al., 2025)*. PHAs have been studied for their promising properties (e.g., biocompatibility, biodegradability) and have been proposed for different medical applications such as scaffold design (Sanhueza et al., 2019), wound dressing (Erci & Sariipek, 2023; Volova et al., 2019), tissue engineering (Mohammadalipour et al., 2023), and drug encapsulation (Vilchez et al., 2021). Saccharides such as levan, pullulan, and fructooligosaccharides produced by *Zymomonas, Gluconobacter,* and *Aureobasidium* species have been studied due to their biocompatibility, biodegradability, antioxidant and antimicrobial properties, which are useful for applications in the pharmaceutical, cosmetical, and food industries (Mulla et al., 2023; Singh et al., 2023b; Teixeira et al., 2023).

However, their production volume and mechanical properties are still not comparable either to conventional polymers or to polymers extracted from biomass, and therefore, they are commonly studied when blended with starch, PLA, PVA, or

PCL, which may enhance their availability, mechanical and physicochemical properties, and biodegradability (Fernandes et al., 2024).

Non-biobased polymers Biodegradable non-biobased polymers can mobilize carbon released to the surface as fossil-based polymers into the carbon cycle through mineralization, contributing to the left cycle (Fig. 15.4). Polyvinyl alcohol (PVA) is a synthetic and water-soluble polymer, whose industrial uses include textile, paper, adhesive, 3D printers, and biomedical applications and can be degraded by some mixed cultures of *Pseudomonas*, *Alcaligenes,* and *Sphingomonas* (Chiellini et al., 2003; Kawai & Hu, 2009). In addition, PVA is commonly blended with starch, polyvinylpyrrolidone (PVP), pectin, alginate, and dextran, to enhance the mechanical properties of films, nanofibers, gels, and other biodegradable materials (Cano et al., 2016; Huang et al., 2019; Suhasini et al., 2023; Phulmogare et al., 2024; Sam et al., 2021). Additionally, polycaprolactone (PCL) is a hydrophobic, blend-compatible, and biocompatible polyester obtained from caprolactone polymerization with potential use in biomedicine and packaging materials. Nanofiber mats can be prepared using PHB/PCL for loading biocompounds and may be used as wound dressing (Erci & Sariipek, 2023). Moreover, PCL has been used to develop microneedles for drug release (Oliveira Filho et al., 2024) and has been tested as a smart packaging material in the form of nanofibers for monitoring the deterioration of food (Oliveira Filho et al., 2024). Finally, poly(butylene adipate-co-terephthalate) (PBAT) is a thermoplastic polyester, whose mechanical properties are comparable to low-density polyethylene. Some applications in biomedical, food, and agricultural fields have been reported. PBAT films are flexible and useful as pouches, mulch films, or garbage bags (Roy et al., 2024). As packaging material, PBAT can be loaded with essential oils for the preservation of foods (Pattaraudomchok et al., 2024) and shows a faster degradation rate when it is blended with another biodegradable polymer such as polyglycolic acid (Fu et al., 2024).

15.6.2 Economic Challenges and Opportunities

The cost of producing bioplastics increases from 4 to 15 times the cost of producing conventional plastics, which is one of the major reasons why these biopolymers are not competitive with petrochemical plastics (Kosseva & Rusbandi, 2018). This economic difference is mainly due to fermentation, extraction, and purification that are less cost-effective. Nevertheless, this reality may change due to advances in research and technology, along with the instability of petroleum prices. Besides, the use of agro-industrial wastes as raw material for bioplastics production has been studied for both, to diminish the costs of bio-based polymers production (Talan et al., 2020) and to diminish the cultivation land needed to produce the raw materials. Different economic/social effects have been studied in the projected future where bioplastics may substitute current conventional plastics to different extents (Jin et al., 2023). Bioplastic production decreases greenhouse gas (GHG) emissions and the depletion

of natural resources if renewable raw materials, adequate labeling, disposal, and closed degradation systems are employed (Walker & Rothman, 2020; Ali et al., 2023). Also, the bioplastic industry may increase land use and job gains, depending on the local and regional economy and its capability to establish a bioplastic industry. However, the implementation of a bioplastic industry depends on the capability to develop infrastructure for establishing a local bioplastic production. The bioplastics industry may contribute to job creation by generating employment opportunities in sectors such as biotechnology, recycling, biorefinery, and agriculture. However, vulnerable stakeholders require recognition and protection to promote a sustainable circular bioeconomy (Blum et al., 2020). For example, financial, technical, and scientific support can be extended through public policy to stakeholders with strategic activities for regional or local economy (e.g., feedstock producers) that can contribute to the bioplastic circular bioeconomy. A systemic approach that addresses technical, economic, environmental, and social sectors through key drivers is essential to develop a framework that enhances bioplastic circular bioeconomy development and sustainability (Parveen et al., 2024).

Furthermore, the energy needed to produce bioplastics is lower than that of petrochemical-based polymers. For example, the total life cycle of low-density polyethylene (LDPE) requires 81.8 MJ kg^{-1}, polypropylene needs nearly 86 MJ kg^{-1}, while PLA or PHB requires 54.1 and 44.7 MJ kg^{-1}, respectively (Costa et al., 2023). This significant difference also has a positive financial and environmental impact.

15.6.3 Industrial Biotechnology of Bioplastics and Added-Value Compounds

Next-generation industrial biotechnology to produce bioplastics and other added-value compounds encourages the usage of biological polymerization, low-cost feedstocks, low freshwater consumption, and contamination-resistant processes to reduce economic and energetic costs (Fig. 15.5) (Rosenboom et al., 2022). This challenge has been addressed with microorganisms resistant to high salinity or capable of metabolizing diverse substrates including non-conventional low-cost substrates (Yu et al., 2019). Halophilic bacteria of the genus *Halomonas* have been used to produce PHA in unsterile seawater-based systems (Tan et al., 2011; Ling et al., 2019). Production of PHAs, ectoine, levan, or pyruvate by *Halomonas* under a salinity of 10–13.7% w v^{-1} of NaCl has been reported; these conditions are useful to prevent contamination (Erkorkmaz et al., 2018; Ma et al., 2020; Ye & Chen, 2021; Dubey & Mishra, 2022). The acidophile *Acidiphilum cryptum* was grown at pH 3.0 to produce PHB and exopolysaccharides from glycerol (González et al., 2023). Xenobiotic-degrading bacteria have been applied to produce PHA homo- and co-polymers from C8–C12 alkanes, benzene, toluene, and phenylacetic acid (Crisafi et al., 2022).

Low-cost substrates Microbes catabolize a wide range of substrates to synthetise a variety of polymers and added-value compounds. The use of strategic low-cost substrates obtained from local industry minimizes economic and environmental impacts associated with raw material transport and processing (Fig. 15.5) (Rosenboom et al., 2022). Grape pomace is a waste/by-product stream from the winery industry, accounting for 20–30% of grape mass, whose high content of sugars impacts ecosystems if not adequately treated (International Organization of Vine and Wine (OIV), 2019). PHB and cellulose have been produced from grape pomace as a substrate by *Bacillus subtilis*, *Cupriavidus necator,* and *Halomonas*, respectively, generating co-products such as oils and polyphenols useful for medical and pharmaceutical applications (Kovalcik et al., 2020; Kurt & Cekmecelioglu, 2023). Lignocellulosic biomass is obtained as surplus streams of different industries and is constituted by cellulose, hemicellulose, and up to 35% of lignin, which is highly recalcitrant (Govil et al., 2020). Lignocellulosic biomass has been used to produce poly(butylene adipate-*co*-terephthalate) and poly(butylene succinate) building blocks (Sohn et al., 2022). On the other hand, *Paraburkholderia or Pseudomonas* strains produce PHAs from sugars and aromatic compounds derived from lignocellulosic hydrolysates (Al-Battashi et al., 2022; Salvachúa et al., 2020). Lignocellulosic biomass from agro-industrial hydrolysate wastes/by-products as paddy straw, wheat straw, corn cob, and wood represents high potential to produce bioplastics (Naitam et al., 2022). The usage of raw materials of photosynthetic origin allows bioplastic production in a closed carbon cycle (Mukherjee & Koller, 2023). Countries with agricultural or forestry activity are suitable to establish this scheme, with bioplastic applications in crop fields and production lines, reducing economic and environmental impact in feedstock and transport (Rosenboom et al., 2022). Similarly, synthesis of starch, PHAs, and added-value compounds by microalgae with wastewater as low-cost substrate decreases GHG emissions up to 50% compared to the fossil counterpart (Kuppan et al., 2023).

Glycerol is obtained from the waste/by-products stream of biodiesel production and is a carbon and energy source to produce PHAs or a plasticizer for cellulose and starch (Zhu et al., 2013). Fish-canning wastewater with high salinity has been used to produce PHAs in non-sterile systems, reducing approximately 25% of environmental impact related to the treatment of this stream (Roibás-Rozas et al., 2020; Palmeiro-Sánchez et al., 2021). The synthesis of PHAs from diverse low-cost substrates as waste frying oil, sugarcane molasses, cheese whey, and coffee waste has been reported (Marciniak & Mozejko-Ciesielska, 2021). Bacterial diversity is a useful source of catalysts to address challenges of raw materials to establish an industrial biotechnology tuned with local and regional circular bioeconomy (Możejko-Ciesielska et al., 2023).

Microorganisms possess the anabolic potential to synthesize added-value compounds as antioxidants, antimicrobials, or antitumoral drugs. The recovery of these compounds from waste streams or microbial biomass with a biorefinery approach adds value to the down-stream processes, promoting circular bioeconomy schemes (Fig. 15.6) (Kumar & Verma, 2021). The establishment of biorefineries can increase

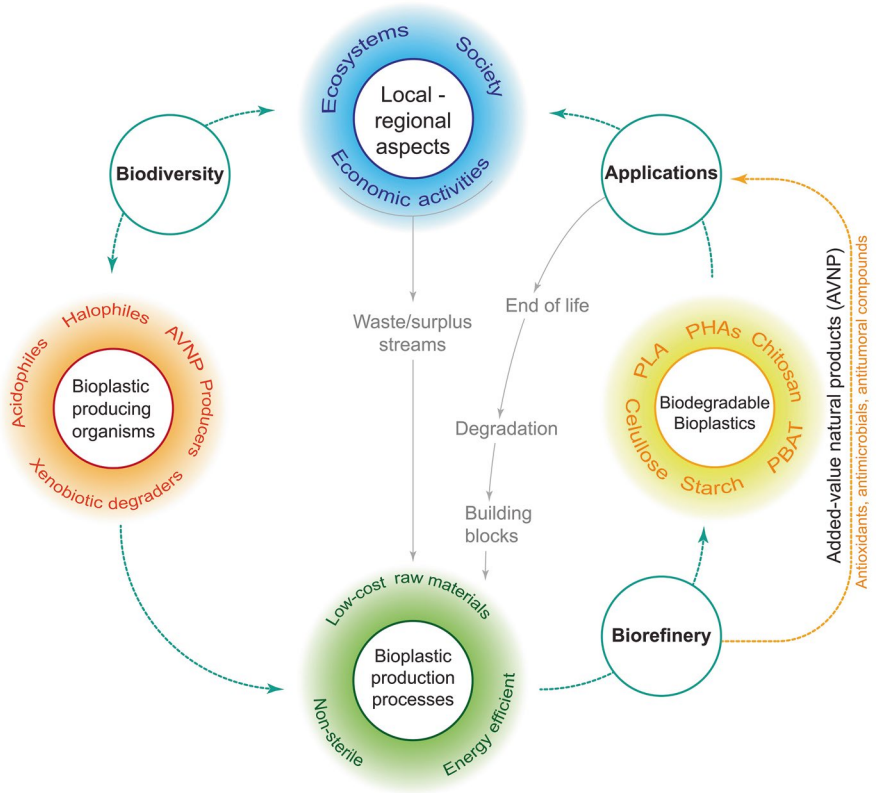

Fig. 15.6 Bioplastic production in a circular bioeconomy scenario. Local-regional aspects: society develops in a local-regional economy placed in ecosystems that harbor specific biodiversity. Polymer producing organisms: specific biodiversity harbors organisms of biotechnological interest with useful features for sustainable bioplastic production. Bioplastic production processes: organisms of biotechnological interest possess metabolic and physiological capability for establishing low-cost bioplastic production by using non-sterile systems or waste/surplus streams from local-regional economy as feedstocks to produce bioplastics and added-value natural products (AVNP). Biodegradable bioplastics: biological biodiversity offers a wide range of bioplastic, while AVNP may be obtained in a biorefinery scheme, increasing value-chain of bioplastic production. Biorefinery of bioplastics and AVNP represent a synergy that may be enhanced by combining bioplastic with AVNP that possess antioxidant or antimicrobial activities, broadening bioplastic applications according to local-regional requirements.

up to 2% of employment; however, countries with GDP per capita below €27,231 are less benefited due to the lack of infrastructure (Zhu et al., 2024). Antimicrobial and antioxidant compounds as curcumin, caffeic acid and pigments have been used in combination with different bioplastics for applications in tissue engineering as wound dressing, bone implants, or in personal protection elements (Ignatova et al., 2018; Vilchez et al., 2021; Lee et al., 2022). Microorganisms from different ecosystems (e.g., marine water and sediments, marine organisms) are a promising source of novel added-value products such as antibiotics or enzymes (González et al., 2020; Cumsille et al., 2023).

15.7 Concluding Remarks

Biotechnology meets the challenges of circular bioeconomy development by transforming waste into valuable resources through sustainable processes, reducing environmental impact, and promoting more efficient uses of natural resources.

Innovating in the improvement of bioremediation strategies through the valorization of local waste provides significant advantages, both for the bioremediation processes, by promoting the survival of microorganisms with metabolic capabilities for contaminant removal, and for the circular bioeconomy, contributing to the closure of the life cycle of products of commercial interest. Due to the growing number of contaminated sites worldwide, as well as the physicochemical nature of each polluted site, bioremediation faces the constant challenge of designing site-specific strategies that adapt to specific contaminants and environmental conditions. Otherwise, agriculture faces complex and multi-dimensional challenges that have been addressed through the development of bioproducts that gather the features to improve the sustainability of food safety. The bioproducts, biofertilizers, microbial biocontrol agents, and botanical compounds are essential to achieve a sustainable and resilient agriculture. Bio-based biodegradable bioplastics are suitable for the design of sustainable products whose lifecycle can be integrated into socioecological systems, although their mechanical or physical properties and production costs are still not comparable to the fossil-based counterpart. Microbial diversity provides alternatives for the biorefinery of bioplastics and natural bioproducts from biomass and wastes/by-products, which may be integrated into a local and regional circular bioeconomy, contributing to additional jobs and the sustainability of ecosystems.

Government support and collaborative research by investigators, farmers, and industrial stakeholders are critical to the effective development and application of bioproducts. Emerging research topics, responsible science-based approaches, collaborative efforts, investment in technologies, and balanced regulation in green policies will be crucial for the development of biotechnology that promotes a circular bioeconomy.

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Chapter 16
Plastic Pollution: Challenges and Strategies

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16.1 Introduction

16.1.1 Importance and History of Plastics

Since their invention in the early 1900s, plastics have become increasingly widespread throughout global society. So much so that plastics now permeate all aspects of our technology and environment in massive volumes. Indeed, the importance of plastics in the biocircular economy can be seen by the names that have been applied to our modern global society. Geologically, some have proposed to call our current age the "Plasticene" epoch (Rillig et al., 2023). Similarly, historians, who have often classified human history as consisting of the Stone Age, the Bronze Age, and the Iron Age, have speculated that we currently live in the Plastic Age (Thompson et al., 2009).

The word plastic existed long before the age of modern plastics. The word itself is derived from the Greek word plastikos, used in ancient times when referring to

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unhardened clay and other materials that were pliable and easy to mold. The first synthetic plastic, called Bakelite, was invented in 1907 by Leo Hendrik Baekeland. Although similar "plastic" materials had been made in the 1800s, Bakelite is considered the first true plastic in the modern definition because it is 100% synthetic (i.e., not based on any naturally occurring components).

Although plastics had some use as components in radios, building construction, and other materials in the early 1900s, they became much more widespread in the 1950s and especially the 1960s. By 2020, more than 367 million metric tons per year was being produced globally, with an estimate that this amount will triple by the year 2040 if current rates of growth are projected forward (Lau et al., 2020).

Modern plastics are made of synthetic organic polymers with chain-like molecules made of repeating chemical structural units. This structure creates plastic's commercial appeal from its vast chemical versatility combined with many desirable physical properties: low cost, durability, and lightweight. As a result, plastics now permeate all elements of the global economy (Barrowclough & Birkbeck, 2022). While the most common plastics include various kinds of polyethylene, polyvinyl chloride, polystyrene, and polypropylene polymers, there are now hundreds of different types of plastics often used in thousands of products ranging from packaging, clothing, buildings, synthetic chemicals, and paint (Fraser, 2022). Currently, the largest market for plastic is packaging, accelerated by a global shift from reusable to single-use containers (Geyer et al., 2017).

16.1.2 Environmental Impacts of Plastics

Currently, the vast majority of plastics are made from organic polymers derived from petroleum sources that are very resistant to degradation in the environment. Unfortunately, because of its extreme durability, caused largely by the lack of microbes able to degrade petroleum-based polymers, it has been suggested that all of the conventional plastic ever made is still not fully degraded unless it has been burned (Thompson et al., 2005).

Predictably, this massive volume of plastic waste combined with its durability has produced one of the largest environmental problems facing humanity. For example, the share of plastics in municipal solid waste (by weight) increased from less than 1% in 1960 to more than 10% by 2005 in middle- and high-income countries (Jambeck et al., 2015). But a vast amount of discarded plastic ends up in the environment, especially the oceans where it is found in all habitats, from shorelines to remote islands to the deep sea and even Arctic sea ice (Napper & Thompson, 2020). Indeed, it is estimated that 75% of all marine litter is plastic and this litter causes over $18 billion in global damages per year (Napper & Thompson, 2020, 2023). Even lakes and rivers are increasingly accumulating vast quantities of plastic (Eerkes-Medrano et al., 2015).

The impact of all this plastic on living organisms, including humans, is enormous. As noted in their review of global plastic environmental impacts, Napper and Thompson (2023) group these impacts into three basic categories: 1) impacts on

fauna and flora, 2) economic consequences, and 3) impacts on human health and well-being. Plastic impacts on fauna and flora largely occur via: entanglement, ingestion, and chemicals (Napper & Thompson, 2023). Chemical effects are especially harmful as they include a very large suite of toxic effects from nano- and microplastic particles that cause harm at many scales, ranging from intracellular levels up to bioaccumulation across entire food webs. Microplastics and nanoplastics are plastics with particle sizes <5 mm. They form when larger plastic pieces are exposed to erosion, degradation, photo-thermal oxidation, UV degradation, or friction (Li et al., 2018).

Economic impacts include monetary losses that reduce natural capital and ecosystem services of all types that degrade biodiversity and ecosystem function caused by plastic pollution (Napper & Thompson, 2023). Impacts on human health and well-being are especially associated with the chemical effects of nano- and microplastics noted above. These are indicated by many studies showing large amounts of these plastic particles occurring in virtually all human tissues and organs (Prata et al., 2020; Napper & Thompson, 2023).

A possible way to mitigate the plastic problem is to reduce the use of plastic or utilize plastics that break down more quickly into less harmful components. For a truly biocircular economy, the goal would be a relatively rapid and complete microbial conversion of all plastic waste in the environment to carbon dioxide, new microbial biomass, and mineral salts under oxic conditions or to carbon dioxide, methane, new microbial biomass, and mineral salts under anoxic conditions (SAPEA, 2020). Such "biodegradable" plastics have been under development for several years. But many studies show that the degradation rate of such plastics in soil and water is disappointingly slow (e.g., Napper & Thompson, 2019). However, research on these biodegradable plastics is nonetheless progressing, especially in the use of agricultural plastics.

16.2 Plastic Usage in Agriculture and Crop Production

16.2.1 Plasticulture

Plastics are commonly employed for crop cultivation, a practice often referred to as "plasticulture." Examples of agricultural plastics include mulch and silage film, bale wraps, row covers, landscape fabrics, high- and low-tunnel covers, irrigation piping, drip tape, and packaging for plants, fertilizers, and other agrochemical inputs (Table 16.1 and Fig. 16.1). The global use of plastics in agriculture was reported to exceed 6 million tons annually in 2019 and was projected to reach 9 million tons by 2030 (Le Moine & Ferry, 2019).

Mulch films are the most abundantly used plasticulture implement, with an estimated market value of $11.5 billion in 2021; this value is estimated to reach $15.7 billion in 2026 at a compound annual growth rate of 5.6%. Mulch films are thin (~20–100 μm) and are typically purchased in rolls of height ~ 1.2 m. Plastic mulches

Table 16.1 Features of conventional plastic materials employed for agricultural applications[a,b]

Product	Composition	Additives	Service life, yr	Contamination, wt %[c]
Mulching films	LDPE, LLDPE, PEVA	Colorants[d], UV stabilizers	0.5[d]	60–80
Low tunnel films	LLDPE, LDPE	UV stabilizers, IR absorbers, anti-fog agents	0.5[d]	60–65
High tunnel films	LDPE, LLDPE, PEVA/PEBV	Colorants[c], UV stabilizers, silica filler, anti-dripping, -dust, and -fog agents, IR absorbers, stabilizers for resistance to agrochemicals	1–2.5	15–20
Silage, bale wrap, and shrink films	LLDPE, PEVA, PP, LLDPE	Colorants[d], UV stabilizers	1	NA
Fumigation tarps	HDPE, LDPE, EVOH layer, vinyl or neoprene-coated nylon	Colorants[d], UV stabilizers	>1	NA
Solarization films	PE	Clear	0.5[d]	Significant
Row covers and landscape fabric	PP, PET	Colorants[d], UV stabilizers	0.5–3	NA
Agrochemical containers	PET, LDPE–HDPE	Colorants, UV stabilizers, thermal resistant additives	1	NA
Irrigation pipes	LDPE, HDPE	Colorants[d]	10–20	NA
Drip tape	LLDPE, HDPE LLDPE	Colorants[d], UV stabilizers	1	NA
Fertilizer sacks	PE, PP	UV stabilizers[d], colorants	1	NA

[a]Adapted from Astner et al. (2023); data provided from Briassoulis et al. (2013), Zhu et al. (2018), GreenPro (2021), Global Plastic Sheeting Inc. (2023), Townsend (2018), Stapleton et al. (1997), Gill et al. (2009), Birthisel et al. (2018), Traunfeld (2023), USDA-NCRS (2024)

[b] Abbreviations: *EVOH* ethylene vinyl alcohol, *HDPE* high-density polyethylene, *IR* infrared, *LDPE* low-density polyethylene, *LLDPE* linear low-density polyethylene, *NA* data not available, *PE* polyethylene, *PET* polyethylene terephthalate, *PEVA* polyethylene-co-vinyl acetate, *PEVB* polyethylene-co-vinyl butyral, *PP* polypropylene, *PVC* polyvinylchloride, *UV* ultraviolet

[c]Refers to the weight of primarily adhering soil (contamination) on the film surface relative to the film dry weight after one growing season; common contaminants include soil and organic matter (e.g., residues of herbaceous plants, straw, and hay)

[d]E.g., carbon black or TiO_2

are typically machine-laid on raised beds of soil (MarketsandMarkets, 2021; von Moos et al., 2012). After mulch films are laid, holes are placed in the films for planting seeds or seedlings. Plastic mulches enhance the production of vegetables, small fruits, and other specialty crops through their creation of a microclimate underneath the film. Mulches reduce weed formation, minimize soil erosion and evaporative loss of water (thereby enabling drip irrigation), and control soil temperature (Serrano-Ruiz et al., 2021; Steinmetz et al., 2016; Hayes et al., 2019; Kasirajan and

Fig. 16.1 Plasticultural implements: (**a**) mulch film; (**b**) silage film; (**c**) high tunnel; (**d**) row cover; (**e**) drip tape; (**f**) irrigation tape. Photos courtesy of Annette Wszelaki, Brooke Keadle Emery, and Douglas Hayes

Ngouajio, 2012). The color of the film helps modulate the latter, with black films promoting soil warming and white films leading to soil cooling.

Films are also employed for high tunnels (HTs), also referred to as "hoophouses," which are less expensive alternatives to greenhouses, composed of thicker plastic films compared to mulches (80–220 mm thick, 20 m wide) that are placed over steel framing (Espí et al., 2006). Unlike greenhouses, which typically have ventilation controlled actively through electrical ventilation systems, the air temperature and ventilation are controlled passively, through opening and closing side flaps (Donovan et al., 2023). HTs are employed for specialty crop production to extend the growing season relative to outdoor cropping, allowing for earlier planting and later crop harvest and they may increase crop yields (Donovan et al., 2023). Similar to mulch films, HTs control a microclimate underneath them, protecting crops and soil from extreme weather events such as flooding (Donovan et al., 2023). However, irrigation must be used. HTs have been employed mostly in colder climates for season extension; however, HTs are gaining interest in warmer climates to mitigate floods and droughts (Wallace et al., 2012; Donovan et al., 2023). The implementation of HTs requires extensive management of flap positions, solar energy retention, and nutrient and water management for optimal performance in cropping (Zheng et al., 2019). To encourage improvement of soil health, the USDA Natural Resources Conservation Service (NRCS) started a new program in 2009 to provide cost-sharing funds for US farmers for the purchase of HTs and to provide guidance on their use (Donovan et al., 2023). Related to HTs are low tunnels, which are less expensive alternatives prepared using small metallic or polyvinylchloride (PVC) hoops and slightly lower thickness (80 μm) (Espí et al., 2006).

Silage films, also known as bale wraps, are plastic sheets designed to protect chopped up forage plants such as corn, hay, and grasses from moisture, oxygen,

heat, sunlight, aerobic bacteria, and mold and preserve the nutrient value of silage for storage over the winter months or during dry seasons, for use as animal feed (Eyouagro, 2024; Western Packaging, 2021). The films are typically composed of multiple layers, with the outside layer being puncture- and tear-resistant and white, to reflect solar radiation, and the inner layer being black to further block light transmission to the silage that would undesirably inhibit anaerobic fermentation. The film must possess good elongation properties to stretch over the forage, providing an air-tight seal. In addition to bales, silage film can be laid directly over silage pits and trenches. Silage films are available in several different thicknesses, to address diverse climates and uses.

Polymeric films are also employed as fumigation tarps, where fumigation involves the use of pesticides to eliminate insects, rodents, fungi, and other pests from soil, stored grain, food products, and wood products (GreenPro, 2021; Global Plastic Sheeting Inc., 2023; Townsend, 2018; Ontario Crop Protection Hub, 2024). Common pesticides include methyl bromide, chloropicrin, and metam sodium for soils, 1,3-dichloropropene to control nematodes, phosphine for stored grain, and sulfuryl chloride for eliminating termites. Fumigation tarps are much thicker than mulch or HT films: typically ≥100 μm, flexible, are impermeable to the transport of pesticide vapors, thereby entrapping the pesticides, and are used typically for 1–2 weeks for soils and 1–3 days for other applications. Guidelines for pesticide use should follow those developed by government agencies, such as the US Environmental Protection Agency (U.S. EPA, 2024). Often fumigation tarps contain multiple layers, including a low-permeability layer such as polyethylene vinyl alcohol, and are available in many different colors.

Within the same category as fumigation tarps are solarization films, where solarization leverages summer sunlight and clear films of ~50 μm thickness to increase the temperature of soil to ~45–55 °C up to 5 cm in depth, eliminating weeds and soil-borne pests such as insects, diseases, nematodes, and fungi for small farms and gardens (Stapleton et al., 1997; Gill et al., 2009; Birthisel et al., 2018). Solarization is a more sustainable substitute for fumigation in organic agriculture but must be used for several (~2–7) weeks successively.

Floating row covers provide protection for berries, fruit, and vegetable crops from frost, wind, insects, and animals (e.g., deer, groundhogs, and birds), thereby improving crop yield and quality and extending the growing season (Mahr, 2024; Traunfeld, 2023; Dhakal & Nandwani, 2020; USDA-NCRS, 2024). Unlike the films discussed above, row covers are typically spunbond nonwoven fabrics (geotextiles), where nonwovens are textiles consisting of randomly oriented microfibers or filaments, bonded either by friction, cohesion, and/or adhesion (Yilmaz et al., 2020). Spunbond nonwovens, prepared by combining filament spinning and web formation steps followed by the thermal bonding process, typically possess relatively large microfibers of average diameter 15–20 μm (ÇİNÇİK & İNan ÜStÜN, 2022; Yilmaz et al., 2020). Spunbond materials cover more than 50% of the nonwovens market (6.3 million tons in 2020) and are employed in diverse applications such as clothing, hospital protective wear, automobile parts, and diapers (ÇİNÇİK & İNan ÜStÜN, 2022; Yilmaz et al., 2020) (and references therein).

Spunbond materials provide a high mechanical strength per weight ratio. The films can be placed directly on top of the plants or can be laid over framing (i.e., similar to low tunnels). Row covers typically are categorized into three groupings: 1) light-weight (~15 g m^{-2}; 90–95% of light transmittance, 1 °C of frost protection), which protect against insects throughout the growing season, 2) medium weight (17–34 g m^{-2}, 70–85% of light transmittance, 2–3 °C of frost protection), and 3) heavy-weight (150–75 g m^{-2}, 30–50% of light transmittance, 4 °C of frost protection) (Traunfeld, 2023). Although rainwater will penetrate through the row covers, for hand-watering it is best to pull the row covers back or use drip irrigation under the row covers. Row covers should be stored in a dark, cool, and dry storage facility and covered with black plastic film between uses. Row covers may become damaged during severe weather and may lead to excessive heating underneath the cover.

Similar to row covers, landscape fabrics are geotextiles designed to prevent weeds and soil erosion near trees and shrubs, in flower beds, and underneath rock gardens and gravel paths (Purnell, 2023; Plank, 2024). Landscape fabrics are either nonwoven or woven and made of the same polymeric materials as row covers. Drip Tape consists of strong, thin (0.2 μm), and flexible plastic tubing used for the application of low and consistent dosages of water to plant roots over several months (Haghparast et al., 2022; Yang et al., 2023). Drip irrigation conserves water usage compared to traditional irrigation methods and reduces plant diseases, hence it is integral in many organic and sustainable agricultural operations.

The most common materials for plasticulture are low and high-density polyethylene (LDPE and HDPE, respectively), along with linear LDPE (LLDPE), where the latter possesses lower levels of branching in the molecular structure (Table 16.1) (Hussain & Hamid, 2003; Scarascia-Mugnozza et al., 2011; Kasirajan & Ngouajio, 2012). LDPE alone accounts for 2 million tons of plastic usage in agriculture alone (Serrano-Ruiz et al., 2020). The popularity of PE is because of its low cost, excellent mechanical and chemical properties (e.g., high tensile and tear strength, elongation, durability, chemical inertness, and low gas permeability; Table 16.2). However, PE is also poorly biodegradable, although the scientific community is in pursuit of robust microbial degraders of PE (El-Sherif et al., 2022; Zhang et al., 2022). In addition, recycling of agricultural films is only at 30%, hindered by the high cost of labor for retrieval and transport of used PE films to collection sites, high contamination levels of soil and toxicants (e.g., phthalate-based plasticizers and adsorbed heavy metals and pesticides) on the retrieved plastics, and heterogeneity and presence of other components in the PE films (Table 16.1) (Serrano-Ruiz et al., 2021; Steinmetz et al., 2016; Hayes et al., 2019; Korol et al., 2021). As a result, used LDPE films have been mishandled by illegal burning, which leads to air pollution, by on-farm stockpiling, which leads to degradation and fragmentation of the films, or by burial in soil, which can produce micro/nanoplastics (Astner et al., 2023; Dong et al., 2022; Huerta Lwanga et al., 2023; Kasirajan & Ngouajio, 2012). Yet, upcycling of used agricultural plastics to prepare polymers and fuels is a current research focus (Korol et al., 2021; Hofmann et al., 2023). Other traditional plastics used for agricultural applications include polypropylene (PP) and polyethylene-co-vinyl acetate (PEVA) (Table 16.1).

Table 16.2 Properties of commonly used polymers in agriculture, as well as emerging biodegradable polymers[a,b]

Polymer	Properties	T_g (°C)	T_m (°C)
Conventional polymers; low biodegradability			
LDPE	Hydrophobic, good vapor barrier, high tensile and tear strength	−78	105–115
PET	Strong and light-weight, low gas permeability, recyclable	67–81	250–260
PEVA	Semi-crystalline polymer useful for shape-forming applications, such as cabling and flexible packaging	(−30)–(−23)	45–100
Biodegradable polymers			
PBAT	Good thermal stability and mechanical properties; brittle	−30	120
PLA	High modulus and tensile strength, low elongation break, brittle, high T_g	60–65	150–160
PBS	Good thermal and chemical resistance	−28.5	116.4
PHA	Good UV resistance, poor mechanical properties, poor resistance to acids and bases	2–8	160–175

[a]Table obtained from Astner et al. (2023), with data from Bugnicourt et al. (2014), Wang and Deng (2019)

[b]Abbreviations for polymers is given in Table 16.1; T_m and T_g refer to the melting and glass transition temperatures, respectively, with the latter referring to the temperature at which the polymeric material changes morphology from a hard/glassy state of an amorphous polymer to a soft state

16.2.2 Biobased Versus Biodegradable Plastics

The terms "biobased and biodegradable" are often misunderstood in relation to agricultural plastic, thereby creating confusion. Biobased plastics are derived "… in whole or significant part of biological products or renewable domestic agricultural materials (including plant, animal, and marine materials) or forestry materials" (US Senate Committee on Agriculture Nutrition and Forestry, 2006). In other words, biobased refers to the beginning-of-life for materials. The biobased content of a plastic can be measured through stable carbon isotopic analysis, e.g., ASTM D6866, leveraging the higher ^{13}C and ^{14}C content in renewable carbon compared to fossilized carbon (ASTM International, 2012a). In contrast, biodegradability refers to a substance's end-of-life, specifically, the breakdown of plastics via microbial assimilation into simple molecules such as CO_2 and water for aerobic biodegradation and CH_4 and CO_2 for anaerobic biodegradation, and microbial biomass (ASTM International, 2011a). Biodegradation must be referenced to 1) a biodegradation environment (e.g., activated sludge, fresh or seawater, soil, or compost), 2) a threshold value of biodegradation (i.e., conversion of the plastic's carbon atoms into CO_2 or CH_4), and 3) a threshold duration (e.g., a few weeks to several months).

Inherent biodegradability should therefore be referenced to criteria listed in a standard; e.g., ASTM D6400 and EN 17033, pertaining to biodegradability of plastics under industrial composting conditions and of plastic mulch films in soil, respectively. The two standards specify achievement of 90% biodegradability in 180 days and 2 years, respectively, using the ASTM D5338 and ASTM D5988 testing methods, respectively (ASTM International, 2012b; European Standard, 2018;

ASTM International, 2011b, 2012c). The latter methods simulate the biodegradation environment under controlled laboratory conditions and specify the use of control treatments to provide context for assessments.

Biodegradability is completely unlinked to biobased content (Hayes, 2017). For instance, PE mulch, although typically prepared from fossil fuels, can be derived from sugarcane (Suarez et al., 2023). Both fossil fuel-derived and biobased PE are equally recalcitrant to biodegradation. Moreover, inherent biodegradability is attributable to the molecular bonds present in the plastic, where ester, acetal, ketal, and amide linkages, for instance, are readily biodegradable, whereas C-C single bonds present in PE are poorly assimilated by microorganisms. The small difference in isotopic composition between renewables and fossil-based materials is small and is not expected to impact biodegradability to any significant extent.

16.3 Biodegradable, Alternative, and Biobased Plastics in Crop Production

While the benefits of using plastic mulch in crop production are evident, the disposal issue remains a challenge. If disposed of properly, growers must pay for the labor to remove the mulch from the field, transportation costs to and from the landfill, and in some places a tipping fee for each load taken to the landfill (Velandia et al., 2019)—not to mention that once in the landfill it remains there for many years (Wojnowska-Baryla et al., 2022). Oftentimes, due to the added time and expense of transporting to the landfill or challenge of finding a landfill that will accept agricultural plastic, plastic is stockpiled on the farm (Fig. 16.2) or burned. While plastic

Fig. 16.2 Stockpile of plastic mulch on a tomato farm in Northeast Tennessee, USA. Photo courtesy of Annette Wszelaki

burning is legal in several states, it poses health and environmental hazards, such as air pollution, toxic emissions, particulate matter, soil and water contamination, greenhouse gas emissions, and incomplete combustion (Michael, 2024). The hazards have been linked to cancer, immunological issues, and birth defects, as well as increased risks of heart disease, respiratory issues, and neurological disorders (Pathak et al., 2024). Unfortunately, recycling is not a viable option due to the transport costs of mulches to recycling centers, mixed plastic resin types, sporadic availability of the mulches, and contamination with soil, plant material, and other farm inputs. Therefore, alternatives to traditional polyethylene mulches are needed.

Biodegradable plastic mulches were introduced in the 1970s and 1980s (Moore & Wszelaki, 2016), with the idea that instead of having to pull up the mulches and dispose of them after the production season is over, growers could till them into their soil at season's end and they would break down within 2 years. Regrettably, the first iterations of these mulches were expensive and misnamed. They were photodegradable mulches, which are made with polyethylene and break into smaller pieces of plastic when exposed to UV light, but do not break down and remain in fragmented form for many years in the field (Kasirajan & Ngouajio, 2012). Consequently, biodegradable mulches were not widely adopted and gained a bad reputation.

Since that time, many advances have been made in the formulations of biodegradable plastic film mulches. These films are made of corn starch and other biodegradable polymers (Martin-Closas et al., 2003). Truly biodegradable mulches, once tilled into the soil, are capable of being broken down via microbial activity through oxidation of the parent compound to carbon dioxide, water, and microbial biomass (Numata et al., 2009). Therefore, if they can be applied similarly and perform similarly to traditional polyethylene mulches—by helping to manage weeds, conserve moisture, reduce disease, and improve crop quality and yield—as well as do no harm to the soil and aquatic environment, biodegradable plastic mulches could be a viable, more sustainable alternative to traditional plastic mulch.

Biodegradable plastic mulches have been tested on a wide range of small fruit and vegetable crops and under varying environmental conditions (Martin-Closas et al., 2017). Among crops tested on biodegradable mulch, cucumber (Wortman et al., 2016), eggplant (Waterer, 2010), grape (Hostetler et al., 2007), lettuce (Lopez-Marin et al., 2012), pepper (Moore & Wszelaki, 2019b), tomato (Miles et al., 2012), and zucchini (Waterer, 2010) were found to yield similarly to polyethylene mulch. Sweet potato was found to also yield comparably or better when grown on biodegradable versus polyethylene mulch. Other crops, such as melon (Lopez-Marin et al., 2007; Fillippi et al., 2011; Vetrano et al., 2009) and strawberry (Andrade et al., 2014; DeVetter et al., 2017), were found to yield as well or better or not as good on biodegradable mulch as they did on polyethylene mulch. While pumpkin (Ghimire et al., 2018), raspberry (Krol-Dyrek & Siwek, 2015), and sweet corn (Rajablarijani et al., 2014; Waterer, 2010) were shown to have decreased or similar yields when grown on biodegradable mulch compared to polyethylene mulch.

These variable results are dependent on the crop cultivar studied, biodegradable mulch selected, its color, and its constituents, planting date, and geographic location. Vetrano et al. (2009) compared seven cultivars of winter melons and found that

the cultivars performed differently on the mulches, with some yielding lower on the biodegradable mulches, some yielding equally, and others yielding higher on biodegradable mulches compared to polyethylene. Fillippi et al. (2011) compared melon production on black and green biodegradable mulches with black polyethylene and found that the green mulch yielded higher than either black mulch. Furthermore, Rajablarijani et al. (2014) grew sweet corn on black polyethylene and a semitransparent biodegradable mulch. In the first planting in early June, corn grown on black plastic had higher yields than corn grown on semitransparent biodegradable mulch, but by the July planting, yields were comparable. In the case of pumpkin, Ghimire et al. (2018) found that of the six mulches they tested (polyethylene mulch, four biodegradable plastic mulches, and a paper mulch), yield varied by location and mulch with three of the biodegradable mulches yielding similarly to polyethylene mulch and one biodegradable mulch yielding less pumpkin fruit than the polyethylene in the cool climate of NW Washington State. All of the mulches tested outyielded the bareground treatment (no mulch) and all but one of the biodegradable plastic mulches had higher yields than the paper mulch treatment. However, in the hot, humid Southeast in Knoxville, Tennessee, all of the mulches yielded similarly. The average soil temperature in Tennessee was higher than in Washington, which suggests that geographic location is important and mulching might not increase yield in warmer regions, but can provide other benefits like weed management or soil moisture retention.

Weed management is another critical component where biodegradable mulches must perform similarly to polyethylene mulch, as weed control in vegetable and small fruit fields can be very time-consuming and if not managed, weeds can overwhelm the crop, reducing overall yield. Similar to yield, weed management can vary by crop, mulch thickness, and mulch degradation. Generally, weeds need to be managed during a critical weed period—the time during a crop lifecycle when weeds must be managed to avoid significant yield loss (Jones et al., 2024). This can vary by crop, for example, some crops like okra, cabbage cauliflower, radish, and cucumber have a critical period of 4 weeks in which the crop must remain free of weed competition, while tomatoes have a critical period of 6 weeks, and the critical period for onion is the entire production season (Chaco & Sheeja, 2021). Therefore, it is critical that the biodegradable mulch remains intact during these critical weed periods and does not start to degrade too quickly. Mulch breakdown can also be influenced by weather. Rainy weather early in the season, before the mulch is covered by the crop leaf canopy, can hasten mulch degradation (personal observation).

To ensure that biodegradable mulch does not break down too quickly, growers can work with the manufacturer so that they have the proper mulch thickness for their crop and environment. In addition to biodegradable plastic mulches, there has been much attention focused on paper mulches in the USA. However, paper mulches do not possess the same attributes as the biodegradable plastic mulches in that they do not have the black color that provides soil warming early in the season, they tend to degrade more quickly, especially in a wet environment or year, they can be harder to lay with a mulch layer, and they are heavy. Their weight can add a considerable expense in shipping costs, as well as necessitate the rolls to be made much shorter

(500 ft long vs 2000–4000 ft long for standard plastic mulches) and, thereby, need to be changed much more frequently, which adds time and labor. Paper mulches can perform well in a dry year and provide control of nutsedge, a destructive weed, as nutsedge cannot penetrate the paper, due to its composition and thickness, while nutsedge can penetrate both polyethylene and biodegradable plastic mulch (Moore & Wszelaki, 2019a, 2019b). In recent years, hydromulch is another paper-based alternative that consists of shredded newsprint paper, water, and a tackifier that is being studied and can be made on-farm (Ahmad et al., 2024). Hydromulches result in a liquid slurry that is sprayed onto the soil and dries into a mulch mat. These mulches show promise for weed control as well as strawberry yields; however, large-scale application technology still needs to be developed.

While they do not meet all the criteria that growers desire, paper mulches are allowable in certified organic production systems in the USA according to the National Organic Program (NOP) because they are 100% cellulose and biodegrade quickly (Miles et al., 2017). Although the NOP added biodegradable plastic mulches to the list of allowable substances in 2014, there is still no biodegradable plastic mulch that meets the other requirements set forth for these products (Miles et al., 2017):

1. The polymer feedstocks to make biodegradable mulch must be completely bio-based (current biodegradable plastic mulches are between 10% and 20% biobased).
2. The mulch must reach 90% biodegradation in the soil within 2 years or less as evaluated using standardized tests (This is influenced by temperature, sunlight, moisture, and mechanical stresses and field tests indicate that biodegradable mulches may not reach 90% biodegradation within 2 years in some locations.)
3. The mulch must meet compostability specifications of ASTM D6400, ASTM D6868, EN 13432, EN 14995, or ISO 17088.
4. The mulch must be produced without organisms or feedstocks derived from excluded methods. (This includes starch feedstocks from GMO corn or sugar beets, microbial fermentation feedstocks from GMO yeast or bacteria, and minor additives.)

The USA lags behind the European Union and China in adopting policies to help curtail the agricultural plastic issue. China, for example, has introduced more stringent standards on the minimum thickness for non-biodegradable mulch to aid in retrieving it from the soil (FAO, 2021). The European Union has banned oxo-degradable mulches due to concerns of microplastics (European Union, 2019). Furthermore, in several countries, including Spain and Italy, biodegradable plastic mulch use is incentivized, aiding in its adoption. While in the USA, the Natural Resources Conservation Service has a one-time payment incentive through their Environmental Quality Incentives Program, it is on a year-by-year and state-by-state basis and not widely known (NRCS EQIP, 2024). Although there is interest in adopting biodegradable plastic mulches, the higher initial cost—two to four times the cost of polyethylene—prevents many growers from trying these mulches. Beyond the initial cost of the biodegradable mulches, other economic

considerations are outlined below. As these products become more widely available and understood, costs could decrease and growers will have the benefits of black plastic mulch, with the ease of tilling them into the soil at the end of the production season, providing a more sustainable production system.

16.3.1 Economic Considerations of Biodegradable Mulch

Assessing the economic feasibility of adopting biodegradable mulches (BDMs) versus traditional polyethylene (PE) mulches is a complex process. Factors, like labor costs, the type of workers (e.g., H-2A workers vs. domestic workers), the price of BDMs, and disposal regulations, are central to determining whether switching to BDMs makes sense for farmers:

16.3.1.1 Labor Costs and Type of Workers

Labor plays a crucial role in the overall cost structure of any farm. Farmers need to account for the labor required for both removing and disposing of PE mulches, as well as the labor associated with the more careful handling of BDMs. Some critical points to consider:

- *H-2A Labor*: The cost of H-2A labor can be high, especially when factoring in recruitment, housing, and transportation costs (Roka et al., 2017; Yu et al., 2024). Furthermore, because H-2A workers are seasonal workers when eliminating plastic removal activities, there might not be other activities the workers could do if the farm is not diversified. Therefore, the workers will be sent home earlier. That could affect the relationship between the worker and the employer. The workers could look for alternative employers that will employ them for a longer period of time (Velandia et al., 2018).
- *Labor Shifts*: Transitioning to BDMs could change labor requirements. Based on a survey of Tennessee vegetable growers and interviews with three Tennessee vegetable growers, Velandia et al. (2019) found that removal and proper disposal of PE mulch took an average of over 18 h per acre versus slightly over 2 h to remove drip tape and till BDMs into the soil. Therefore, any potential increase or decrease in labor hours must be taken into consideration.

16.3.1.2 Price of BDMs

The cost of BDMs is another critical factor in the feasibility of adoption. BDMs are often more expensive than PE mulches. However, they offer the advantage of biodegradability by being tilled into the same field in which they were laid at season's end. The trade-off between the higher initial costs of BDMs and any potential

savings from the reduction of labor use associated with removal and disposal activities, reduced disposal costs, and the avoidance of costs or fees associated with not complying with environmental regulations related to the use and disposal of plastics could affect the farm's bottom line.

16.3.1.3 Environmental Regulations and Disposal Costs

As regulations surrounding plastic waste become stricter, the cost of disposing of PE mulches could increase (Velandia et al., 2019). If future regulations reduce the options available for PE mulch disposal or increase the costs of disposal, this could tilt the economic balance in favor of BDMs.

16.3.1.4 Potential Long-Term Benefits

An important limitation of previous studies evaluating the economics of adopting BDMs is the lack of inclusion of the value of potential environmental benefits that could have impacts on the long-term profitability of the farm operation (Yu et al., 2024). For example, when removing PE mulches, some topsoil attaches to the mulch and is lost when disposing of the mulch. Over time, the productivity associated with topsoil loss might need to be compensated with other inputs, implying an additional cost, and if not compensated, it might result in soil productivity loss (Velandia et al., 2018). Other studies suggest that the high concentration of PE mulch fragments in the soil could result in a reduction in crop productivity (Liu et al., 2014). No study, as far as we know, has evaluated the economic value of the potential long-term benefits associated with the adoption of BDMs at the farm level (Yu et al., 2024).

16.4 Challenges: Health, Persistence, Incomplete Degradation, and Solutions

The increasing awareness of environmental issues has led to a growing interest in biodegradable and biobased plastics as alternatives to conventional plastics. These materials are designed to reduce the environmental impact associated with plastic waste, particularly in terms of pollution and resource depletion. However, despite their potential benefits, biodegradable and biobased plastics face several significant challenges that hinder their widespread adoption and effectiveness. Addressing these challenges is crucial for improving the sustainability of these materials and mitigating the problem of microplastic pollution in soils.

Biodegradable and biobased plastics present promising alternatives to traditional plastics, but they face several challenges. As mentioned, a major issue is their high

production cost, which stems from the expensive raw materials and complex manufacturing processes involved. Additionally, these plastics often exhibit limited performance, such as brittleness and lower mechanical strength, which restricts their applications. Another significant problem is that biodegradable plastics may not fully degrade in natural environments, leading to the formation and persistence of microplastics. The persistence of microplastics in the environment may have an impact on soil food webs and ultimately human health. Furthermore, the production and degradation processes of these plastics can still contribute to greenhouse gas emissions.

The fate of plastics in the environment is driven by the interaction of fragmentation and degradation processes. Fragmentation occurs as a combination of natural and human-induced processes. Over time, larger plastic items, such as agricultural films, packaging, and other plastic debris, break down into smaller fragments due to environmental conditions like ultraviolet (UV) radiation from sunlight, temperature fluctuations, and moisture cycles (wetting and drying), which contribute significantly to the degradation process. UV radiation causes photodegradation, which makes plastics brittle and prone to breaking apart (Anunciado et al. 2021). Similarly, temperature changes and moisture cycles cause both soils and plastics to expand and contract, leading to physical stress and eventual fragmentation. Mechanical forces also play a crucial role in the fragmentation of plastics in soils. Activities such as tillage, plowing, and other agricultural practices apply physical pressure to plastic materials, causing them to break into smaller pieces (Bhattacharjee et al. 2023). Additionally, the interaction with soil organisms, such as earthworms and insects, can further fragment plastics as these organisms burrow and move through the soil (Adhikari et al. 2023).

As biodegradable plastics fragment in field soil, they form microplastics (Sintim et al., 2019; Griffin-LaHue et al., 2022), which can behave differently in soil than the larger macroplastic particles (De Souza Machado et al., 2018; Lehmann et al., 2021). It's expected that smaller plastic fragments will be more quickly biodegraded due to their higher specific surface area (Tosin et al., 2019; Huo et al., 2024), but changes to the materials, such as size, density, shape, and surface charge, or interactions with soil particles as plastics fragment into smaller pieces, may also slow degradation rates (Astner et al., 2023).

Agricultural ecosystems are part of the natural environment and affect the food web, as well as indirectly affect human beings. As mentioned earlier, farmland is a source pool of microplastics due to frequent human activities (plastic film mulching, tillage, and fertilization), and thus microplastics are likely to migrate from farmland to food webs (Jin et al. 2022; Fig. 16.3).

Studies on terrestrial mammals and farm animals have found that microplastics and nanoplastics can accumulate in tissues, as well as in animal feces and soil (Beriot et al., 2021; Jin et al., 2022). They can disturb the digestion processes of organisms and tend to bioaccumulate and biomagnify when they are ingested by fauna (Jin et al., 2022). A wide range of impacts of microplastics and nanoplastics on animals have been observed and include digestive system operation, reproductive health, oxidative stress and inflammation, and endocrine disruption (Prata et al.,

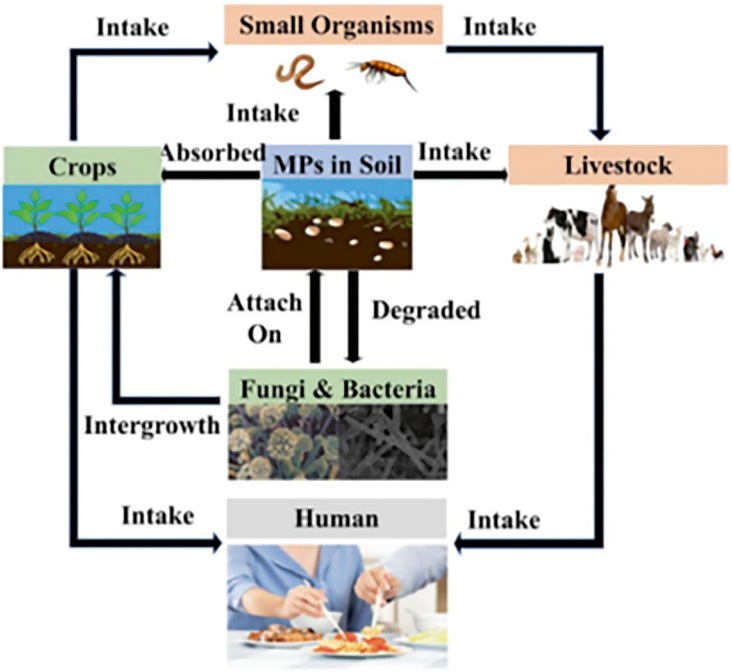

Fig. 16.3 Transmission of microplastics through the food web. Figure from Jin et al. (2022)

2021; Urli et al., 2023). There is also a general concern that plastics can accumulate in various tissues, potentially leading to chronic health problems. This accumulation can also pose risks to humans who consume animal products (Prata et al., 2021; Jin et al., 2022). When present in the soil, MPs can inhibit seed germination and root elongation, physically block root pores, cause oxidative stress, and impair photosynthesis (Mateos-Cardenas et al., 2021; Jin et al., 2022). Furthermore, the presence of microplastics in samples of edible vegetables and fruits suggests that microplastics may flow into the market and end up on human tables, posing a potential threat to human health.

In-field degradation rates of biodegradable plastic mulch products can vary substantially, especially between locations with diverse climates (Brodhagen et al., 2017). Users of this biodegradable plastic mulch can expect large macroplastic mulch fragments to persist for 18 months, or more after tilling plastic into the soil for at least two growing seasons (Beriot et al., 2023). It's necessary to understand the degradation behavior of particular biodegradable plastic mulches in particular climates to ensure their suitability for long-term agricultural use—because plastic persistence along with continual reapplication could have negative consequences for crop production (Liu et al., 2014; Gao et al., 2019) or agroecosystem functions (Li et al., 2014; Lehmann et al., 2021; Bodor et al., 2024). Impacts are material-specific (Lehmann et al., 2021) and concentration-dependent (Yu et al., 2023). MPs

and NPs can also be transported below their incorporation depth by soil fauna or percolating water (Yu & Flury, 2021). Because biodegradation is dependent on microbial activity, which decreases rapidly with depth in most soils, MPs or NPs that migrate vertically may be degraded more slowly than at the surface. However, there does exist the potential for microbial communities that are exposed to these biodegradable materials for multiple years, to begin to degrade these materials more quickly (Bandopadhyay et al., 2018; Gillmore, 2024).

To improve biodegradable and biobased plastics, several strategies can be employed. Innovating new biopolymers with enhanced properties, such as better mechanical strength and flexibility, can broaden their usability. Reducing costs through research into cheaper raw materials and more efficient production methods is also crucial. Enhancing the biodegradability of these plastics in various environments, such as soil, water, and compost, through chemical and biological modifications can help ensure complete degradation. Even given these problems, the alternative: conventional plastic mulch products don't fit well into a circular economy framework for agricultural development. The circular economy framework is a sustainable design approach intended to eliminate waste, unlike a traditional linear system where products are manufactured, used, and then discarded. Creating a circular economy is essential for continued human development within the finite resources afforded by the Earth and is also a key strategy to minimize and mitigate the impacts of climate change (Ellen MacArthur Foundation, 2021). Conventional plastic mulches are designed to be used for a relatively short time (less than 1 year), while the plastic material will persist as waste for much longer periods. More circular product design would favor using renewable product feedstocks, keeping products in use for the longest possible amount of time, and maintaining them at the highest level of quality possible during their life. For plastic mulches, product circularity would be increased by systems like compostable plant-based mulch, recyclable plastic mulch, or durable plastic landscape fabrics that can be reused for many growing seasons.

16.5 Conclusions and Future Directions

Reducing oil-based plastic in the supply chain is a critical element of the biocircular economy. One of the most efficient ways to do this would be through the introduction of rapidly degrading polymers in agriculture and many other industries where plastics are commonly used on massive scales. Reducing microplastic pollution in soils requires a multifaceted approach. Improving waste management systems to enhance recycling and composting infrastructure is essential for the proper disposal and degradation of biodegradable plastics. Developing soil remediation techniques, such as soil washing and bioremediation, can help remove existing microplastics from soils. Public awareness campaigns can educate consumers and industries about the proper use and disposal of biodegradable plastics to prevent environmental contamination. Additionally, implementing regulatory measures to limit the use

of non-degradable plastics and promote biodegradable alternatives can drive significant progress in reducing microplastic pollution. By addressing these challenges and implementing these strategies, we can improve the performance and sustainability of biodegradable and biobased plastics and reduce the impact of microplastic pollution in soils.

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Chapter 17
Circular Bioeconomy Toward Net-Zero Emission Urban Systems Through FEW Nexus Approach

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17.1 Introduction

Circular bioeconomy (CBE) represents an opportunity to transition from linear to circular production models, promoting a balanced relationship between economic systems and environmental outcomes at individual, organizational, and regional decision-making levels. The current discussion is more closely aligned with bioresources and bioecology, involving biomass conversion and ecological optimization of resource use and an increased biodiversity.

Conflicts over the demand for food, energy, and water (FEW) systems go beyond the existence of large-scale natural resources, since the synergy between the FEW nexus depends on government policies that favor sustainability, the valorization of local aspects and functionality for bio-based production, and the environmental footprint established in urban planning. For this prupose, the regulation and monitoring of the production chain of goods and consumption, combined

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with the participation of stakeholder communities, can make urban cycles linked to the CBE viability.

City is a living organism whose demand for FEW symbiosis is increasingly growing and interconnected with human relations, natural resources, and economic factors. The metabolism of cities allows the use of materials for energy generation, optimization of water consumption, valorization of by-products, and food gains. However, this is an ideal scenario among such systems, which does not actually occur, due to conflicts over land use, the need for adjustments to environmental exploitation models, and the intensification of sustainable development to ensure resilience in cities and the health of the population, in addition to economic gains. In this context, the concept of CBE emerges as a renewal of the traditionally rooted linear model, focusing on sustainable production processes, business model redesign, and economic gains.

CBE is integrated into urban systems because it involves reusing by-products from agriculture (biomass), industrial processes (general waste), and the cities themselves (organic and recyclable waste). However, the transition to this new circularity proposal presents challenges due to technological difficulties that municipal managers are not well informed about, since these technologies are used on a business scale and require significant investment to ensure financial returns. The biggest bottleneck of CBE in cities is governance and social participation as they drive the elements of urban cycles. To make CBE economically viable, public policies should be innovated, and exchanges between private initiatives and public authorities should be promoted with the support of technology centers and pilot studies.

CBE is primarily explored through biotechnologies and bioresources. There is still a lack of research into the value chain of bioproducts and gains in land use in traditional systems versus energy generation by biomass. This is in favour of sustainability through CBE modelling, which considers the benefits of water, energy, and food consumption. This can make cities more resilient to climate change and consequently improve quality of life in remote locations.

The main contributions of this chapter are to clarify some aspects of circularity in urban systems by conducting a descriptive literature review and to identify the opportunities and challenges for CBE development from a FEW nexus perspective. Future studies based on this reflection could explore the quantitative connection among circularity indicators, FEW systems, and urban sustainability.

17.2 Circular Bioeconomy in the Cities Toward Sustainability Perspective

Rapid urbanization and prevailing consumption patterns have put unsustainable pressure on socio-ecological systems. Currently, urban systems are responsible for approximately 70% of global carbon emissions, 75% of natural resource consumption, and 50% of solid waste production (Seto et al., 2014). Meanwhile,

the Earth loses around 75 billion tons of topsoil each year. Twenty-five percent of its surface is already degraded (Ellen MacArthur Foundation, 2015). The overexploitation of natural resources and unregulated urban growth have intensified the use of synthetic fertilizers, leading to soil degradation and declining agricultural productivity (Costanza et al., 1997; DesRoches, 2020).

Humanity consumes natural resources at a rate 1.7 times higher than the Earth's regenerative capacity, exceeding planetary boundaries (Rockström et al., 2009; Steffen et al., 2015). The urban population is projected to reach 7 billion by 2050, which will intensify urban metabolic pressures (Ritchie & Roser, 2020). Currently, approximately 3% of global energy is allocated to the pumping and treating water for urban and industrial uses (Zhou et al., 2013). The predominat linear model, which is based on extraction, consumption, and disposal, continues to deteriorate ecological and economic imbalances. The increasing urbanization in the world underscores the urgent need for integrated strategies to reconfigure urban material and energy flows (Chen & Chen, 2017).

Water demand, particularly for agriculture, is another major concern. Studies estimate that 6800 to 7130 km^3 of water will be required annually to meet agricultural needs in the early decades of this century, equivalent to about 3000 liters per person per day. This greatly surpasses the average requirements for drinking water (2–5 liters per day) and domestic use (20–300 liters per day) (Embid & Martin, 2017; Gazzoni, 2011). These trends are driven by dietary shifts toward greater consumption of animal products, fruits, vegetables, sugar, and oils. While agriculture remains the most water-intensive sector, demand is also expected to rise in domestic and industrial contexts.

In the energy sector, biofuel production significantly increases water consumption (Gazzoni, 2011). Producing energy from biomass requires 70 to 400 times more water than equivalent generation from fossil fuels, solar or wind energy. Consequently, water use is closely linked to biofuel consumption, reinforcing the importance of public policies that promote renewable energy and the role of social pressure in the advancement of sustainable energy alternatives.

In response to these challenges, the concept of urban biocycles has been proposed as a strategic framework to reconnect resource flows and natural demands in cities. Based on the principles of CBE, this approach aims to transform waste into valuable resources such as nutrients, energy, and materials, thus promoting a regenerative urban metabolism that harmonizes human and ecological systems (Girardet, 1999; Kennedy et al., 2011). In this way, cities become living organisms focused on metabolic reorganization by valuing organic waste through transformation technologies such as anaerobic digestion, composting, and nutrient recovery.

17.2.1 Transition to Sustainable Systems

Since the early 2000s, several global initiatives have been launched to address extreme poverty, reduce infant mortality rates, combat epidemics, and promote sustainable development. During the 2011 Bonn Conference, the FEW nexus was introduced to promote an integrated and sustainable systems thinking by reducing trade-offs and enhancing intersectoral synergies (Hoff, 2011).

Since 2020, countries have been submitting Nationally Determined Contributions (NDCs) which outline strategies for mitigating greenhouse gas emissions and increasing resilience to climate change. By 2024, the Enhanced Transparency Framework (ETF) has been established to monitor climate action and report on progress via the Global Stocktake process (UNCC, 2024). The 2030 Agenda is structured around five key dimensions—People, Planet, Prosperity, Peace, and Partnership (5Ps) and supports 169 targets that foster the achievement of 17 Sustainable Development Goals (SDGs).

Connecting these dimensions and resilience to climate change is crucial to making cities resilient. Then, the concept of bioeconomy varies in different contexts around the world (Ferreira et al., 2024) and encompasses knowledge of biotechnology, bioresources, and bioecology, especially the latter two (United States, 2022).

CBE focuses on transforming renewable biological resources into high-value products and valorizing bio-waste and by-products (European Commission, 2012, 2018) by preserving agroecosystem health, prioritizing essential human needs, recycling biological outputs, and minimizing energy use through nature-based approaches (Muscat et al., 2021).

Similarly, from a Brazilian perspective, CBE represents a synergistic model that integrates natural resources (biomass) with advanced technologies within a biologically based, clean, and renewable production system (Embrapa, 2023), associating bioeconomy with zero deforestation, social equity, and respect for local cultures and biodiversity. As a result, the term "sociobioeconomy" has been suggested as an inclusive and equitable development grounded in justice, ethics, traditional knowledge, and ecological conservation.

The transition to CBE requires integrated planning across micro, meso, and macro levels. At the micro level, environmentally conscious individual behavior is fundamental; at the meso level, companies must balance ecological sustainability with productivity through efficient resource management; and at the macro level, systemic transformations are promoted by governments and institutions through urban ecological planning and collaborative consumption, supported by monitoring tools (Fig. 17.1).

CBE operationalization can be developed by actions in all three levels, with emphasis on reuse, recycling, and equipment maintenance (micro); interorganizational partnerships boosted practices such as material and energy recovery, especially in the biodegradable caps chain (meso); and all cases analyzed presented low implementation rates, indicating challenges in reducing emissions, energy consumption, and large-scale waste management (macro), according to Tsakalova et al. (2024).

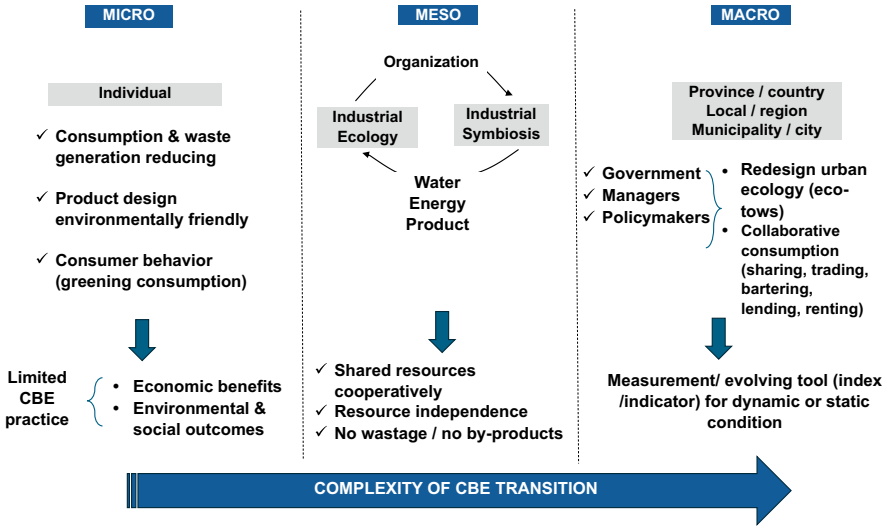

Fig. 17.1 Circular bioeconomy transition approach

This transition is driven by the interplay between technological, financial, ecological, and behavioral factors, which serve as key decision-making elements (Khalifa et al., 2022). Coordinated policies are essential to stimulate financial support for circular innovations and to promote behavioral shifts within enabling ecosystems. These elements function as catalysts for reaching a net-zero ecosystem by 2050 with progress evaluated through dynamic and static performance indicators (Petit-Boix & Leopold, 2018; Silvestri et al., 2021).

The largest consumer (72%) of freshwater in the world is the agrifood systems (UNWater, 2023) which contribute to approximately one-third of global greenhouse gas (GHG) emissions, stemming from agricultural and livestock activities, land use change (e.g., deforestation), and food system processes such as manufacturing, consumption, and disposal (Crippa et al., 2021; Tubiello et al., 2021, 2022).

Bioeconomic value chains represent complex and dynamic systems, in which multiple actors add value from production to disposal of products with multisectoral collaboration, as a relevant factor for optimizing material flows, reducing losses, and promoting circularity (Tsakalova et al., 2024).

17.2.2 Challenges and Opportunities from CBE

The bioeconomy represents a leapfrog opportunity to attract global investment—estimated at US$7.7 trillion by 2030—particularly in food, feed, waste, and energy sectors (WBCSD, 2020). Recycling alone is insufficient, investments in regenerative and bio-based solutions are essential to reduce resource overuse and address planetary boundaries. However, the report highlights that existing barriers to

achieving the necessary transformation are related to financial flows. And to properly assess the full cost of circular bio-based solutions, companies need to consider both the expected additional costs (e.g., investments in new equipment for biomass processing or the higher cost of bio-based feedstocks) and the potential for long-term savings opportunities (e.g., reduced input costs through waste recycling or lower wastewater treatment costs enabled by bacterial wastewater treatment).

CBE is a cross-cutting concept that addresses global challenges such as poverty, biodiversity loss, and climate change, aligned with the Paris Agreement and the Sustainable Development Goals (SDGs). This concept is addressed by Hsiao and Hu (2024) as biological resource regeneration integrated with industrial processes, and therefore effective climate mitigation and adaptation strategies require integration across ecosystems and sectors, including agriculture, forestry, aquatic environments, industry, and waste management (Gomez San Juan et al., 2022).

The impacts of CBE can lead to hunger, land grabbing, and poverty, especially among indigenous peoples, or precarious and exploitative working conditions in biofuel industries (Geary, 2012). Above all, they can trigger higher prices for basic foods and the use of products generated by food consumed by cars and trucks (Sihvonen, 2017).

The intensification of livestock farming and urban agriculture in cities can also generate significant environmental impacts through GHG and water contamination (Clay et al., 2019; Hatab et al., 2019). On the other hand, nutrient recovery from renewable sources is strategic for restoring nitrogen and phosphorus cycles, as well as for reducing public health risks and food insecurity (Dahiya et al., 2018; Ramaswami et al., 2018).

Despite the growing potential of biocircularity in the agriculture, energy and pharmaceutical sectors, companies must first analyze the impact of the bioeconomy in their production chain, before implementing the necessary changes to guarantee sustainability rather than promoting biowashing—a performative approach that fails to achieve true sustainability (Marshall et al., 2023).

The transition to a sustainable CBE involves risks and trade-offs, and policy choices must be carefully assessed for their impact on food security, land use, health, and urban–rural dynamics (Gomez San Juan et al., 2022). In this way, it is essential to change management, systemic thinking, and leadership skills for structuring sustainable models, economic viability, and reducing environmental uncertainties (Srinivasan et al., 2021).

Achieving net-zero emissions by 2050 requires decarbonizing production, reducing CO_2 emissions, and ensuring sustainable growth in urban and industrial systems. Approximately 45% of CO_2 emissions stem from goods production and land use, while 55% are linked to housing and transportation (Ellen MacArthur, 2015).

One of the strategies for achieving sustainability is the adoption of the EARTH principles (Ecology, Authenticity, Resilience, Transformation, and Holism) for transitioning from the conventional economy to the circular bioeconomy (Marshall et al., 2023). For example, energy recovery implementation of solid waste or a biodigester can help find which natural sources are compromised by the bioeconomy on a regional or local scale (E). The waste-to-energy implementation reshapes the

flow of energy, resources, and water consumptions (A), exposes the risks involved and the mitigation measures needed to ensure FEW security (R), and identifies the internal and external obstacles to the transformation of the supply and value chains of bioeconomy with consideration of the access and affordability of technologies involved in the exploration of natural resources such as wood, seeds, oils, among others (T). It is also important to incorporate systemic thinking into individual and organizational decision-making process not only with participation of the communities that will directly benefit from the technologies (H) but also with performance monitoring and preventive analysis of the actions.

In this scenario, biowashing can be triggered by a lack of commitment to the essence of the CBE. Thus, we exemplify the use of such principles in different contexts, such as: 1—illegal extraction of wood from protected forests by companies that strangle sustainability; 2—use of biofuel as a renewable source for large-scale cargo transportation on highways, without preventing adversities from this source when there is a lack of filters and other mechanisms to control environmental pollution; 3—use of conventional fertilizers to increase agricultural production without appropriate technological changes to the resilience of cities and insecurity of water, energy, and food, both in the exploratory production process and in the engagement of suppliers who are disinterested in conservationist and sustainable practices; 4—encouraging consumption of products of unknown and unhealthy origins, in contrast to valuing foods with the support of local farmers who are aware of the need to ensure the longevity of humanity, among others.

The evolution of the CBE toward sustainability can be achieved through the use of renewable sources of energy, rethinking whole industrial process, reusing waste to reinvent products for new purposes, business redesign according to individual skills in decision-making, behaviors, and actions, technology transfer to support a successful transition system, providing new products and services (opportunities), and guarding against problems, pitfalls, and trade-offs (Fig. 17.2).

Another strategy is to adopt the guiding principles for sustainability (Marshall et al., 2023), such as Contextual Responsiveness (adaptation to local and regional contexts); Equity and Inclusion (social justice as a central pillar in the design of bioeconomic policies); Authentic Circularity (prioritization of the recirculation of biological resources instead of the simple replacement of inputs) and Participatory Governance (use of democratic mechanisms to integrate different actors in decision-making).

The authors point out that the challenges of implementing CBE are related to Systemic Complexity (interaction between sectors such as agriculture, industry, energy, and waste requires intersectoral coordination and political-institutional integration), Institutional Misalignment (lack of coherence between environmental goals and regulatory structures hinders the transition), Problems of Innovation and Scaling (many bioeconomic solutions remain in the early stages and face barriers to being widely adopted), and Equity and Social Justice (risk of reproducing social inequalities, especially if the economic benefits are captured by a few actors).

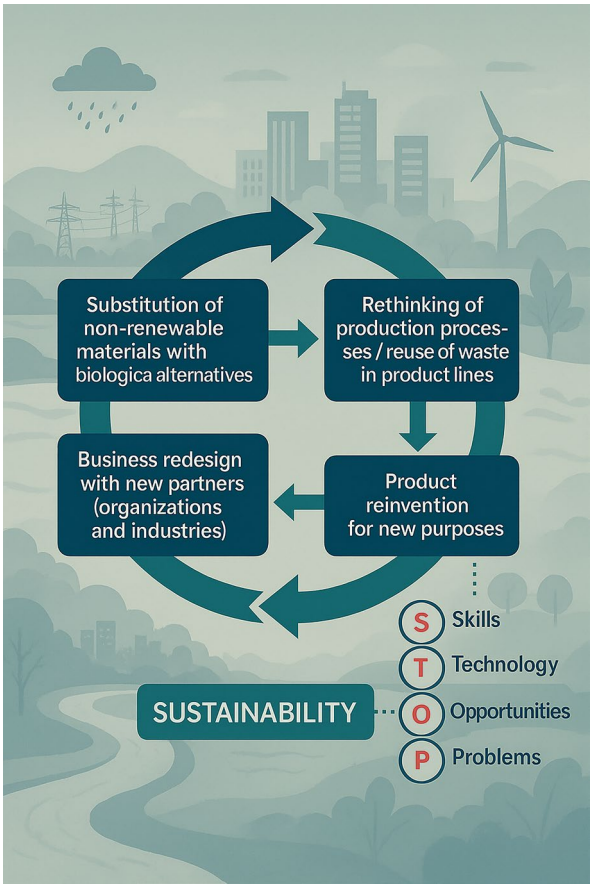

Fig. 17.2 Stages of biocircular transition (adapted from Marshall et al. (2023))

On the other hand, the authors state that opportunities become promising when aiming at Sustainable Regional Development (bioeconomy can promote local value chains, generate employment, and revitalize communities), Substitution of Fossil Materials (Bio-based products can reduce dependence on fossil fuels and carbon emissions), and Technological Innovation (New bioprocessing and biotechnology expand the possibilities for biomass valorization).

Then, challenges and risks are involved in the transition to a sustainable CBE. Although bioeconomy holds significant potential to support climate action, it is essential to evaluate potential trade-offs of policy decisions, especially those affecting food security, land use, human health and safety, and urban–rural interactions, as shown in the examples given in Table 17.1 (Gomez San Juan et al., 2022).

The path to net zero emission by 2050 is underway, as the implementation of cleaner production reduces CO_2 emissions while considering the growing demand for energy to produce goods and maintain resources over time. In these thoughts, it's been necessary to mitigate environmental impact, establish climate change policies, and design an innovation front to live in a sustainable world aligned with economic

Table 17.1 Trade-offs inherent in Urban Circular Bioeconomy (CBE) strategies within the FEW Nexus

Urban CB strategy	FEW trade off	Challenges	Opportunities
Urban vertical farms (Mishra et al., 2024; Kalantari et al., 2018)	Increased energy demand	High initial costs. Energy requirements (artificial lighting and climate control systems). Need for specialized skills	Year-round crop production. Reduced water usage. Minimized pesticide and herbicide use. More productivity per unit of area. Reduced carbon footprint
	Water and land savings compared to traditional farming		
Urban biomass use (Mashhadi et al. 2024; Moomaw, 1994; Biocca et al., 2022; Destek et al., 2021).	Energy required for transport and processing	Cost comparison with fossil fuels. Land allocation and food production	Reduced landfill disposal. Local renewable energy generation
	Local resource recovery		
Greywater reuse (Uddin et al., 2014)	Energy consumption for treatment and distribution	Specific infrastructure. Need for specialized skills	Reduction in freshwater use in gardening and other landscaping. Save the cost of constructing centralized systems
	Savings in potable water use		

development, where cities with a high quality of life are integrated. In this field, about 45% of CO_2 emissions come from land and goods production, while 55% corresponds to residential and transportation sectors (Ellen MacArthur, 2015).

17.3 Study Case Toward Net-Zero: Food, Energy, and Water Transition in the Cities

Climate change heightens the exposure and vulnerability of agrifood systems to shocks and stresses, thereby weakening the ability of stakeholders to prevent, anticipate, absorb, adapt, and transform in response to disturbances (adaptive capacity). Building resilience to such stresses, particularly climatic shocks, is crucial but increasingly challenging under current climate impacts (FAO, 2016, 2021). When resilience is compromised, the risks of acute and chronic food insecurity and malnutrition rise. Ultimately, agrifood system resilience depends on its sustained capacity to ensure the availability of and access to sufficient, safe, and nutritious food for all, despite disruptions (FAO & UNFCCC, 2024).

Urbanization has been recognized as critical to national economic development (Glaeser, 2012). The gross domestic product generated in urban areas exceeds 80%, and urban activities account for more than 70% of global greenhouse gas (GHG) emissions when the cities import fossil fuels and electricity to supply them (Seto

et al., 2014; Field et al., 2014). The energy, mobility, shelter/building materials, food, water, waste management, and green infrastructure/public spaces sectors account for more than 90% of global GGE (Ramaswami et al., 2021; Ramaswami et al., 2016). Beyond that, the world's population that lives in urban areas is expected to increase to 68% by 2050, with nearly 90% of this growth taking place in Asia and Africa (UNDESA, 2018).

The analysis of the possibilities and challenges faced by city managers in reducing of pollutant emissions, especially toward a net-zero-emission future. The challenge remains in cities of the Global South, which need to develop workable and time-bound business models that encourage safe and productive wastewater management and ensure valuable sources of water, nutrients, energy, and precious metals (Hsu et al., 2022).

In a study by the Brazilian Agricultural Research Corporation on the Opportunities and Potential Impact of the Bioeconomy for the Decarbonization of Brazil, researchers suggested sustainable agricultural solutions, such as alternative protein technologies, solutions for livestock confinement, carbon sequestration in soils, new varieties of high-yield vegetables, biological nitrogen fixation (BNF), and biological control (Embrapa, 2023). All solutions refer to optimizing land use and producing biomass with low-carbon emissions or even negative GHG emissions. These solutions have a larger market scale, such as bioenergy with carbon capture and storage, carbon utilization, second-generation ethanol, and biogas.

Another relevant example is the use of biomass and emerging bio-based products—such as biofertilizers, biofuels, wood, soy, bamboo, bioactives, and others—which depend not only on available skills, technologies, and market opportunities, but also on the capacity to identify systemic problems (Marshall et al., 2023). The implementation of such innovations requires investor commitment—both from public authorities and industry leaders—to avoid misleading perceptions of financial investments, potential environmental harms associated with bioproducts, and reputational risks (Baldassarre & Campo, 2016).

The innovations also involve minimizing industrial waste, promoting the extended use of living products through resale or reuse (Todeschini et al., 2017), innovating business models, and designing new products to ensure sustainable land use and reduced waste due to obsolescence (Marshall et al., 2023). Moreover, successful transitions depend on effective organizational reform (Sekerka & Stimel, 2011), including transparent communication, conflict resolution, and the creation of new sectors and systems that integrate environmental, economic, and social dimensions (Gladwin et al., 1995). Public policy is also vital for promoting biocircularity and supporting urban resilience and FEW security (Marshall et al., 2023).

In this context, ecological thinking becomes essential for decision-making and advancing CBE, as it prioritizes the production of high-value goods (e.g., pharmaceuticals) over lower-value outputs (e.g., bioenergy) and emphasizes product life-cycle analysis as a pathway to sustainable bioeconomy development (Sun et al., 2018; Buxel et al., 2015).

A practical example is the German company Prolupin, which uses lupin to produce plant-based alternatives to meat and dairy products, as well as animal feed.

This nitrogen-fixing crop can be cultivated on poor, sandy soils, enriching the soil more than other crops can. This crop is currently grown in the coastal region of Mecklenburg-Western Pomerania in northern Germany (Sun et al., 2018).

Hsiao and Hu (2024) highlighted that biomass can be converted into electricity, heat, biogas, and biofuels for multiple benefits, such as reduced greenhouse gas emissions, regional energy independence, local economic simulation, and enhanced waste valorization. Arun et al. (2020) further underscore the potential of algal biomass in pollution mitigation and renewable energy production.

Cities play a key role in mitigating GHG emissions and achieving the SDGs for human well-being, ecosystem health, social equity, and climate resilience (Ramaswani, 2020; UN, 2017). The potential of cities have not been fully explored (UNDESA, 2020). For example, social inequality is high in many developed cities, where more than 30% of the population generally lives in informal settlements without basic infrastructure (UNDESA, 2020), and is proportionally lower in places with these services.

Residents living in conditions of greater social vulnerability or lacking basic infrastructure may be exposed to an atmosphere highly polluted by fine particulate matter (PM2.5), resulting from fossil fuel energy supply, mobility, and urban construction (Pant et al., 2019; Nagpure et al., 2022), in addition to the burning of urban solid waste (Nagpure et al., 2015) and the spreading of respiratory diseases.

Stressful climate factors (such as heat, floods, hurricanes, and wildfires associated with polluted air) and the lack of access to nutritious food can trigger health conflicts, for example, in relation to the decline in lifespan observed in some neighborhoods of United States cities (Clark et al., 2022; VCU, 2022).

Marshall et al. (2023) identify successful CBE transitions in Finland and Sweden through regional bioeconomy policies, local-scale initiatives such as community biorefineries, and strategies combining circularity, digitalization, and social inclusion to inform EU policies. Hsiao and Hu (2024) cite global examples, including Spain's 2030 Bioeconomy Strategy, Germany's food-first approach, Toyota's Battery 3R program, Neste's renewable diesel, and YFY's biogas from paper waste. Castillo et al. (2023) and Kumar and Verma (2022) emphasize the applications of CBE in agriculture and biorefineries, respectively.

Urban biorefineries convert municipal and food waste into biofuels and bioplastics. In Brazil, the *Exygen I* biorefinery processes sugarcane waste to produce ethanol and biomethane (Click Petróleo e Gás, 2023), while Raízen plans large-scale investments in second-generation ethanol (Biofuels Brazil, 2023). Food waste valorization is economically viable, with projections indicating a market of USD 133.7 billion by 2033 (Bioresource Technology, 2022; GlobeNewswire, 2024).

Lokesh et al. (2018) propose a framework for assessing bio-based value chains focused on organic waste. Pan et al. (2015) and Brosowski et al. (2016) emphasize the importance of supply chain efficiency and the sustainable potential of biomass. Greene (2014), Meyer-Kohlstock et al. (2015), and Hennig et al. (2016) discuss technologies that enhance residue valorization in integrated biorefineries.

Operational success depends on logistics and nutrient recovery (O'Dwyera, 2020; Starck et al., 2023a, 2023b). Biomass offers reliability over variable

renewables, enabling innovations such as bacterial cellulose membranes (Khamwichit et al., 2021), smart agriculture for residue management (Venkatramanan et al., 2021), and shrimp waste valorization for biodiesel production (Nuraliyah et al., 2021; Caetano et al., 2022).

Finally, integrated land and water management is essential, as shown by conflicts between sugarcane cultivation and domestic water use in São Paulo (Oliveira et al., 2022). The land-water integration reinforces the need for balanced resource governance to support sustainable biofuel development.

17.4 Technologies Networks Based on Food–Energy–Water Perspective

Food, Energy, and Water (FEW) nexus approach is a cadenced way to address current and long-term sustainable demands in relation to economic, socio-environmental, and technological issues.

The use of Information and Communication Technologies (ICTs) can strengthen the resilience of FEW systems. The integration of digital and innovative technologies is essential for developing sustainable urban food ecosystems (UFEs) to address the impacts of rapid urbanization and the limitations on land, water, and energy resources (Davies & Garrett, 2018; Jehanzeb, 2024).

About one-third of the world's food is wasted mainly because of its appearance, which could feed two billion people (Royte, 2016). In addition, food loss and waste (FLW) result from other factors, such as socioeconomic factors, improper storage, overpurchasing, labeling confusion, supply chain inefficiencies, dietary shifts, and extended food miles. In addition, high-income consumers reject imperfect produce, while long-distance transport and inadequate storage accelerate food degradation (Sun et al., 2022).

Companies that have opened up markets to reduce food waste and connected food waste to a new marketing chain, such as Food Bank, Imperfect Produce, and Imperfect Picks, have made it possible to consume cheaper, nutritious, tasty, and healthy fruits and vegetables. By buying directly from producers, even if they look like "ugly food," and delivering them to the customer's home, the system results in a 30%–50% price saving compared to supermarkets (Davies & Garrett, 2018).

Technology can help create UFEs, particularly in cases of intense urbanization and high population density. Technological advances in digital devices, enabled by internet connectivity, play a significant role in building these ecosystems, in cases where food production is constrained by a land, water, and energy. Therefore, a food crisis is looming, and the developing world is ill-prepared to feed itself sustainably (Davies & Garrett, 2018).

Addressing transitions in sociotechnical systems requires systemic thinking, as Geels (2005) emphasizes. Bio-based value chains (BBVCs) involve complex interdependencies between actors, material flows, technologies, and regulatory contexts

(Tukker, 2015; D'Amato et al., 2017). These chains prioritize secondary resources—such as sludge, industrial effluents, and organic waste—which demand tailored pretreatment and refining technologies (Pick et al., 2012; Zanghelini et al., 2018).

Technological pathways like anaerobic digestion, composting, nutrient recovery, and fermentation enable the valorization of biogenic waste (Meng et al., 2018). Phosphorus recovery offers environmental benefits (Amann et al., 2018), while biogas utilization advances with urban applications (Angelidaki et al., 2018). Mihelcic et al. (2011) estimated that struvite and biosolids could supply 15%–20% of global phosphorus needs, and Trimmer et al. (2017) suggest urban wastewater could meet up to 12% of global NPK demand by 2030.

A regenerative approach reconnects waste flows with production and soil systems through integrated urban biorefineries (Mohan et al., 2022), co-located with waste treatment plants to produce biofuels, fertilizers, acids, and bioplastics (Dragone et al., 2020; Venkata Mohan et al., 2016). Urban waste biorefinery: innovative integration of waste valorization and resource recovery for a sustainable future (Bioresource Technology, v. 215, pp. 1–13, 2022). Complementary technologies include gas recovery (Khoshnevisan et al., 2019) and the production of biopolymers from urban waste (Meng et al., 2018).

Industrial symbiosis enhances waste reuse across sectors (Albino et al., 2015), as seen in microalgae applications for CO_2 capture, single cell protein (SCP), biofuels, and nutraceuticals (Jones et al., 2020; Khoshnevisan et al., 2019). Hsiao and Hu (2024) highlight the need for alignment among policy, technology, and logistics, while noting data gaps and limited indicators. Nonetheless, their work offers a strong conceptual basis for circular bioeconomy development.

CBE practices require enabling regulatory frameworks and public engagement. Policies must evolve to support the use of recovered resources, while awareness campaigns help overcome social resistance (Rajendran & Han, 2022). Lokesh et al. (2018) identify key barriers, including feedstock seasonality, regulatory gaps, and inadequate post-consumer waste infrastructure. Consumer resistance to bio-based products—due to higher costs and performance concerns—is also highlighted by Spatial Foresight (2017) and Shove (2014).

Biogenic waste streams—food waste, wastewater, and gaseous emissions—can be processed using established technologies such as anaerobic digestion, composting, nutrient recovery, and fermentation (Meng et al., 2018). Amann et al. (2018) underscore the environmental benefits of phosphorus recovery, while Angelidaki et al. (2018) discuss advances in urban biogas technologies.

Taffuri et al. (2023) analyze Turin's fragmented organic waste system, characterized by low material and energy valorization, limited treatment capacity within the urban perimeter, and long transport distances. The study models waste flows directed mainly to composting and anaerobic digestion, with landfilling as a secondary route. The Pinerolo Ecological Hub is a case of integrated aerobic and anaerobic treatment aligned with circular principles (Demichelis et al., 2019).

Using system dynamics, Taffuri et al. (2023) represent feedback loops—reinforcing loops highlight compost's role in soil fertility (Diacono & Montemurro, 2011), bioenergy generation (Mohan et al., 2022; Dahiya et al., 2018), and

bioplastics and enzyme production (El-Bakry et al., 2015), while noting that organic inputs can reduce soil metal contamination (Fassio & Minotti, 2019). Balancing loops involve public policies, co-composting with sewage sludge (Van Timmeren et al., 2007), and behavioral shifts through education and food redistribution (Toldo et al., 2018; Chifari et al., 2017).

Digital platforms are emerging as key tools to address logistical failures in food systems and link waste valorization to precision agriculture. In the USA, technologies such as AI-enabled crop mapping (John Deere, 2024; GreenSight 2023) and microbial solutions to enhance crop resilience and reduce emissions (Pivot Bio, 2024; Indigo Ag, 2024) exemplify this trend.

AeroFarms (2024) specializes in vertical, soilless (aeroponic) agriculture leveraging artificial intelligence, plant biology, and innovative systems to produce flavorful, nutrient-rich vegetables. Their method uses up to 90% less water than traditional farming and 40% less than hydroponics, without the need for chemical pesticides or post-harvest washing. Located in dense metropolitan areas, AeroFarms reduces transport emissions and food waste. The use of recyclable trays and post-consumer recycled plastic films embeds circulatiry.

CIBO Technologies (2024) develops digital tools that promote regenerative agriculture and sustainability. Using satellite imagery and geospatial data, their platform monitors farming practices, tracks supply chain emissions, calculates carbon intensity, and supports soil regeneration and resource conservation. By integrating digital technology with economic tools and nature-based solutions, CIBO contributes to low-carbon urban food systems and helps meet climate targets.

These cases illustrate how digitalization of food systems, coupled with energy-water integration, can inform public policies and investment decisions for carbon neutrality. Governments should prioritize regulatory frameworks that support digital and low-carbon technologies, such as urban aquaponics (e.g., Metro Farm, Singapore), biomass cogeneration (e.g., Denmark), and software platforms such as Indigo Ag, GreenSight, and CIBO. Policy support for electric vehicle infrastructure, district heating from renewables, and energy storage—as in Copenhagen—is also critical for system resilience and emissions reduction.

From an investment perspective, these findings emphasize the need to channel public and private funds into local, integrated energy solutions. Priorities include circular economy projects that recover organic waste for bioenergy, energy-efficient building technologies, and consumer engagement in energy management through peer-to-peer markets. International case studies show that these strategies are viable when backed by consistent policy, R&D support, and innovative business models that deliver socio-environmental value.

Another way to provide sustainable food is precision agriculture, which uses advanced technologies to increase productivity supported by Wireless Sensor Network (WSN), Internet of Things (IoT), cloud computing, Artificial Intelligence (AI), and Machine Learning (ML). This practice increases production yield by 200%–400%, reduces energy use by up to 50%, and water and land use by up to 95% in addition to optimizing the use of pesticides and fertilizers (Davies & Garret, 2018; Shafi et al., 2019).

Some companies and startups work with precision agriculture, especially in countries such as the United States, Tanzania, France, Italy, India, Brazil, New Zealand, Switzerland, and South Korea (Schirmer et al., 2021). For example, platforms like *Taranis* (2024), used in Brazil, Israel, and the USA, enable automated detection of agronomic threats and precise application of fertilizers and pesticides, significantly reducing agrochemical use and improving soil and water quality. In India, *AgroStar* (2024) demonstrates how digital tools and access to inputs and technical support can restore degraded soils, minimize post-harvest losses, and save billions of liters of water by closing nutrient cycles. Companies such as *XFarm* (2025) and *Ecorobotix* (2023) use sensors, AI, and precision spraying systems to drastically reduce water, pesticide, and fertilizer use, thereby reducing the environmental footprint of conventional farming.

On the socioeconomic front, several platforms are reshaping urban production networks. *La Ruche qui dit Oui* (2024) in France connects local producers and consumers through short supply chains, reducing post-harvest losses, energy and water waste, and boosting local economies. Halter (2024) uses virtual fencing for innovative livestock management, supporting carbon sequestration and pasture regeneration with social and environmental benefits. *N. Thing* (2024) offers modular vertical farming systems for urban environments, optimizing resource use and recycling water and nutrients.

Finally, *WeFarm TZ* (2024) connects farmers through SMS and ML, expanding access to technical knowledge and strengthening urban–rural resilience through circular knowledge-sharing networks. Together, these emerging technologies support sustainable urban planning by integrating regenerative practices, digital innovation, and social inclusion.

Davies and Garret (2018) identified 12 innovative technology platforms for the advancement of UFEs, which are (1) connectivity (information delivery platforms and digital technology); (2) uberized services; (3) precision agriculture (Global Positional System—GPS, Internet of Things—IoT, Artificial Intelligence—AI, sensing technology— (ST); (4) controlled environment agriculture; (5) blockchain for greater transparency, food security and identification; (6) solar and wind energy connected to microgrids; (7) high-quality, improved seeds for increased yield, nutrition, climate, and pest resistance; (8) advanced genetics (gene editing, synthetic biology, and cloud biology); (9) biotechnology (microbiome, soil biologicals, cultured meat, alternative proteins to meat and dairy); (10) nanotechnology and advanced materials; (11) 3D printing/additive manufacturing; and (12) integration of new technologies to scale up existing underutilized technologies.

The application of technologies in urban food ecosystems can enhance the resilience of agricultural production, while generating opportunities across the value chain—for instance, through urban food production and the delivery of new goods and services to consumers via more efficient and inclusive distribution systems (Davies & Garret, 2018). Innovation in the agricultural sector involves developing business models that are contemporary to the demands of natural resources (Zhuang et al., 2023).

Thus, technological advances are needed to establish new patterns of solution business models (SBMPs). Schirmer et al. (2021) analyzed 198 digital solutions from 116 agricultural startups and identified 18 SBMPs, outlining the technological drivers for innovation in the farming sector.

In addition to technology, it is essential to promote policies that help develop the next generation sustainable UFEs. It involves land use and ownership, trade, entrepreneurship, access to credit and markets, cooperative structures, government transparency, rule of law, education, and the eradication of illiteracy. Equally important are nationwide investments in agriculture, climate-resilient road infrastructure, reliable electricity and strong local capacity-building and mentorship initiatives (Davies & Garrett, 2018; Mengoub, 2018; Yeboah, 2018). In this context, there are opportunities and challenges within food systems (Table 17.2) that need to be addressed when existing technologies and the need for policies are evaluated.

Similarly, the digitalization of energy systems is developing rapidly, with new computing architectures that increase their usability and resilience, strengthening the transition to net zero. These systems include real-time monitoring and control of electricity distribution networks, enabling functions such as dynamic operation, flexibility markets, and peer-to-peer energy markets. Digitalization plays a crucial role in transforming distribution networks, making them more active and capable of integrating greater levels of low-carbon technologies (Deakin et al., 2024).

Countries such as Germany, Denmark, the United States, the United Kingdom, Japan, and China are advancing global efforts to reduce reliance on fossil fuels by promoting renewable energy sources like wind, biomass, and solar power (Chen & Heilscher, 2024; Quitzow, 2022; Ostergaard et al., 2021; Kangas et al., 2021; Zhang et al., 2023). Technological innovations increasingly reflect the FEW nexus by integrating energy and water systems within the food sector.

In Singapore, Metro Farm (2024) supports sustainable urban agriculture through aquaponics, a system that combines hydroponic plant cultivation with fish farming in a recirculating water system (Kumar et al., 2024). In England, Grid Edge (2024) uses AI-powered platforms, like Edge2X, to optimize energy use in commercial buildings, supporting net-zero transitions. In France, Schneider Electric (2024) applies IoT-based technologies—such as the EcoStruxure platform—to increase energy efficiency and reduce environmental impacts across sectors.

In the USA, Tesla (2024) offers integrated clean energy systems, including solar panels and battery storage (Powerwall and Powerpack), to promote residential and industrial energy efficiency. Additionally, the US Department of Energy's EnergyPlus (2024) software simulates building performance under various climatic conditions, assessing heating, ventilation and air conditioning (HVAC) systems, lighting, and thermal comfort to enhance overall energy efficiency.

In this sense, Fig. 17.3 illustrates the two main approaches that link production and consumption: the Circular Economy and the FEW Nexus. For this connection to be reliable, the digital platform must be based on a reliable system based on the key variables of this chain, such as land use configurations and ecosystem (Producers) as a means of supporting resource demand, behavior change, and solidarity support (Consumers), so that there is optimization in the use of FEW resources.

Table 17.2 Opportunities and challenges of net-zero emission faced by food system

Challenges	Opportunities
Supply a nutritious diet while supporting key policy goals in future food production (Tait et al., 2023) Net-Zero emissions and addressing biodiversity loss (Tait et al., 2023) 26% of GHG emissions in global food production (Ritchie, 2020) Business models for food production and material transformation developed by an integrated perspective (Tait et al., 2023) Complexity of inserting biodegradability and renewability of biological materials in the implementation of the circular economy traditional model (Tait et al., 2023) Difficulty in ensuring the nutritional needs of the population and achieving net-zero emissions objectives in cases of anti-biotechnology perspective (Bjornberg et al., 2015; Willeer et al., 2021) Understanding the mismatches and potential convergence between CE and CBE (Tait et al., 2023)	Replacing fossil-based resources and processes with biological ones to reduce GHG (Gomez San Juan et al., 2022) Reducing GHG emissions through carbon storage in bio-based products and through sequestration of carbon dioxide (CO_2) from the atmosphere through plants and microorganisms (Gomez San Juan et al., 2022) Carbon sequestration in agriculture by microbiome innovations (Gomez San Juan et al., 2022) Reducing methane and nitrous oxide emissions using biofertilizers (Gomez San Juan et al., 2022) Reducing residue management and cascading use against food loss and waste generation (Gomez San Juan et al., 2022) Encouragement for balanced, sustainable, and healthy diets with new food sources (Clark & Lenaghan, 2020; European Commission, 2020) Insertion of protein components into the human diet from sources with lower GHG emissions such as chicken and fish (Clark & Lenaghan, 2020; European Commission, 2020; Gomez San Juan et al., 2022) Minimizing the amount of material for reuse or recycling through an integrated value chain approach (Tait et al., 2023)

The Copenhagen experiences offer valuable lessons for urban transitions that aim to align the principles of the CBE with the FEW nexus and carbon-neutrality goals. Firstly, the systemic integration of energy generation, waste management, and urban mobility stands out, by using solid waste and urban effluents as inputs for cogeneration and biogas production, thereby closing carbon, nutrient, and energy cycles at a local scale (Mathiesen et al., 2015; Damsø et al., 2017; Van Doren et al., 2020; Peštová, 2022).

This approach highlights how residual flows can be transformed into strategic resources, simultaneously reducing GHG emissions and dependence on fossil fuel inputs. Furthermore, the inclusion of citizens as active agents of the energy transition, through policies such as feed-in tariffs and investment in cycling mobility, demonstrates the importance of social participation in enabling circular urban models.

This context is made possible by human–nature interactions linked to demand and supply in a sustainable way (by stakeholders, planners, and experts) based on

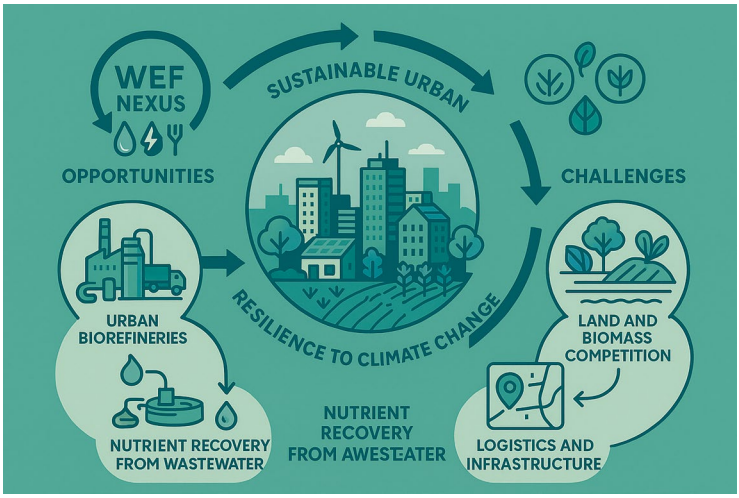

Fig. 17.3 Connecting sustainable urban systems through CBE towards climate-resilient cities

the necessary infrastructure (internet, georeferenced data, innovative technologies, applications, and digital devices) so that this chain (Circular Economy—FEW Nexus) makes the net-zero emissions goals viable (Fig. 17.4).

The investment in integrated technologies—such as electric vehicles, charging stations, energy storage, and biomass-based district heating systems—reveals that achieving net-zero targets requires urban infrastructures that connect traditionally isolated sectors, such as waste, energy, transport, and sanitation (Mathiesen et al., 2015; Damsø et al., 2017; Van Doren et al., 2020; Peštová, 2022). Thus, Copenhagen exemplifies how coherent public policies, combined with technological innovation and participatory governance, are fundamental to enabling circular, resilient, and carbon-neutral cities.

The technology above reduces food loss, streamlines demand between production and consumption, makes the production chain more efficient, and integrates the food, water, energy, and nutrition sectors at the systems level. Besides the opportunities these initiatives offer, there are challenges that must be addressed. These include ensuring flexibility and timely energy supply using renewable energy sources, managing fluctuations in their production, integrating energy sectors, and implementing long-term planning for the development of high-efficiency transport infrastructure. Furthermore, the establishment of comprehensive guidelines and strategic plans at the regional and national levels is essential (Mathiesen et al., 2015).

The United States is developing a carbon-free electricity grid by 2035, with a forecast of net zero emissions by 2050. To achieve this goal, there has been robust investment in technology, in addition to mandatory innovations in this sector, together with effective integration of different existing solutions (Arent et al., 2022).

Opportunities exist and are related to the national system promoted by governments. If there are initiatives to convert polluting energy supply processes into clean

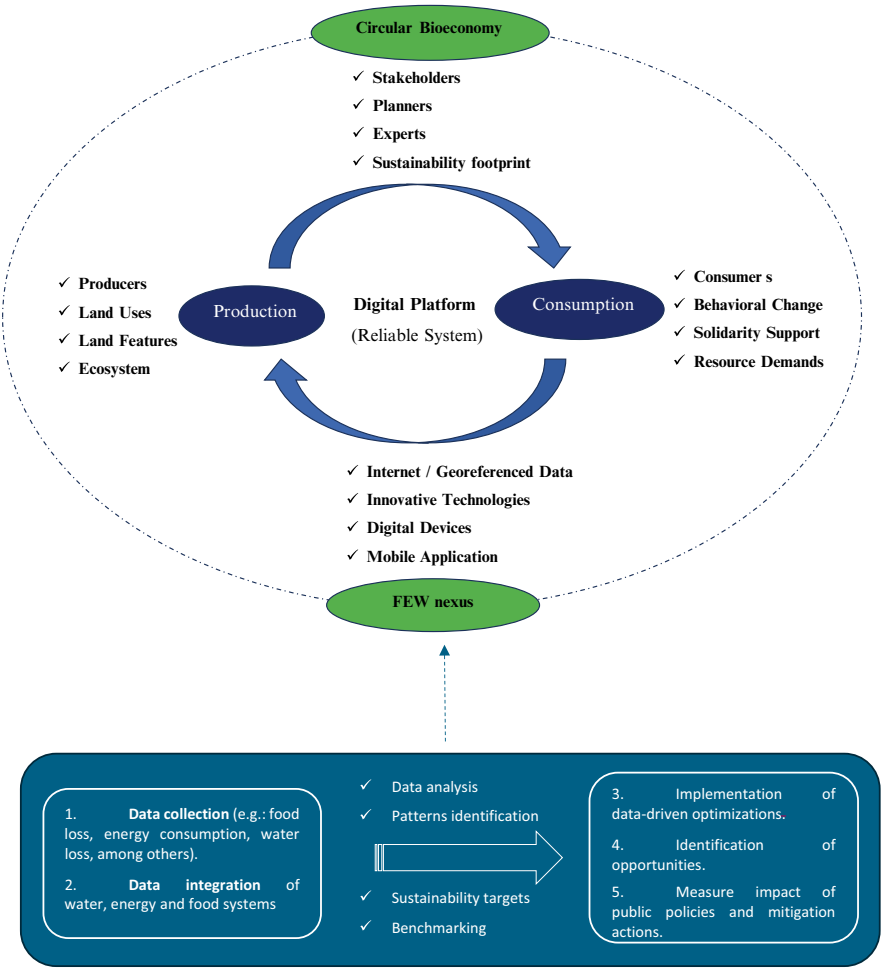

Fig. 17.4 Digital platform interface between producers and consumers towards sustainability--zero carbon emissions

mechanisms, local companies and users can develop solutions. In this sense, clean technology proposals can emerge to help achieve the SDG goals. Meanwhile, some energy transition procedures require robust infrastructure to balance energy reserves and distribution simultaneously.

The pursuit of net-zero emissions offers opportunities for technological innovation and for society's energy systems. However, both negative impacts and benefits are inherent aspects of analyzing opportunities over time. In this sense, a study of sectoral carbon emissions in 30 Chinese provinces from 2007 to 2017, Zhao et al. (2022) found that transitioning energy from fossil-fuel-based energy systems to renewable sources is necessary to reduce carbon emissions, but this transition will not yield immediate results.

The short-term transition entails significant socioeconomic impacts and, in the long term, promotes positive demographic and geopolitical effects on economic growth and the well-being of the population. Therefore, the way forward is to expand viable investments in these technologies and implement a profound reform in the energy system to achieve this goal (Zhao et al., 2022). In this case, the authors mention high-efficiency, low-emission combustion technologies, high-efficiency catalytic conversion of carbon-based energy technologies; and technologies for renewable energy use, such as hydrogen, solar, and wind, among others, for carbon neutrality or sequestration.

There are some challenges to face net-zero emissions in the energy system, such as (i) Impacts of net GHG emissions by the grid electricity decarbonizing (Xiu et al., 2023); (ii) Fuel exchange for bioenergy waste without socioeconomic impacts (Gomez et al., 2022); (iii) Biological treatment of organic waste (straw, manure, food, sewage sludge) for renewable energy recovery (Xiu et al., 2023); (iv) Government constraints (administrative, political, economic) in addressing emissions, particularly for power utilities on a sustainable basis (Hsu et al., 2022); (v) Challenges in the local planning process due to existing infrastructure, economic issues, sociocultural constraints, supply chain complexity, and societal benefits (Arent et al., 2022).

17.5 Optimizing Models for Urban Ecosystem Services and Net-Zero Transitions

Urban ecosystem services (UES) are the benefits provided by natural systems to urban societies, contributing to the enhancement, maintenance, and recovery of environmental quality and, consequently, urban well-being. A key challenge is the mismatch between accelerated urbanization and the sustainable provision of these services. Achieving sustainable UES outcomes requires optimizing of FEW supply chains through integrated urban planning strategies.

Elliot et al. (2019) addressed this issue by applying a multi-objective integer linear programming (MOILP) model that incorporated stakeholder participation to generate spatially optimized solutions for different land-use/land-cover (LULC) configurations in Lisbon, Portugal. Their study analyzed 30 urban systems, evaluating ecosystem services related to flood protection, local climate regulation, and biodiversity. These services were assessed by land economics experts using a scale from 1 (inelastic) to 3 (highly elastic), with a fourth category for infeasible options. The findings indicated that increasing land cover diversity enhances UES performance relative to most other LULC classes. Moreover, the stakeholder involvement facilitated transdisciplinary and interdisciplinary approaches to optimization, bridging mathematical modeling, and spatial planning.

The optimization process resulted in improvements across all LULC types, with the most significant enhancements observed in flood protection, followed by local

climate regulation and biodiversity. While promising, the model presented four limitations: insufficient thematic detail in urban LULC maps, lack of temporal granularity, omission of non-linear interactions and synergies among UES, and inadequate representation of human–nature system dynamics (Elliot et al., 2019).

Temporal resolution is particularly relevant in addressing the needs of evolving demographic and economic contexts. Since the effects of land use changes on UES are not immediate, the complexity of causal modeling increases. For instance, while shrubland may offer immediate recreational value, the associated biodiversity benefits may only emerge in the long term.

As such, the MOILP model is limited in its ability to capture non-linear trends in services like biodiversity. To address this, Boumans et al. (2015) propose the adoption of System Dynamics (SD) modeling, which is well-suited to simulating delayed and dynamic feedback in ecological systems. SD has been widely applied in ecosystem service assessments, as it enables the mapping and quantification of service provision over time using empirical data (e.g., biomass yield in tons per hectare per year) (Boumans et al., 2014; Boumans et al., 2015). Such quantitative approaches improve the understanding of UES synergies and temporal trajectories, offering valuable insights for advancing net-zero urban development.

Land use and temporal details are examples of input data to be structured, for example, by SD, considering the FEW nexus and current public policies, to simulate the benefits and opportunities of achieving the net-zero emission goal (Fig. 17.5).

Future projections underscore the substantial impact of land use transitions on carbon dynamics. For instance, Chen et al. (2023) demonstrated that converting unused land into agricultural areas in northeastern China significantly increased carbon emissions, while Li et al. (2023) observed similar effects from urban encroachment into agricultural zones in Wuhan. In Lisbon, Elliot et al. (2019) emphasized that including stakeholders and experts in optimization modeling enhances the potencial for carbon sequestration during land use/land cover (LULC) transitions.

In Changxing County of China, Liu et al. (2022) showed that optimized, simulated land-use scenarios outperformed official plans in both emissions reduction and economic efficiency. Wu et al. (2022) analyzed Chengdu's LULC evolution from 1990 to 2020, revealing that built-up areas were the primary sources of carbon emissions, while forests served as the most effective carbon sinks, surpassing grasslands

Input	Foundation	Outcome
• Spatial & temporal details • Regional & local scales • Vegetation • Landscape in change • Land use land cover (LULC) • Geographic features	• FEW nexus • Set of efforts (governmental policies, entrepreneurs, users, people) • Optimization Programming	• Net Zero commitment • Socioeconomic benefits from rational land use • Evidences simulation • Global warming awareness by sustainability

Fig. 17.5 Outcomes from optimization model and environmental restraints

and water bodies. Their projections from 2020 to 2035 indicated an expanded role for natural landscapes in carbon mitigation, though this was challenged by urban expansion into farmland. Wang et al. (2024) proposed a multi-objective optimization model for Hubei Province that integrates carbon suitability, historical land use, and socioeconomic drivers. Their simulations projected effective carbon sequestration by 2030 and 2060, supporting the feasibility of harmonizing low-carbon development with economic growth.

As geospatial modeling evolves, ecological, economic, and carbon-based criteria are increasingly integrated into land-use optimization frameworks, enabling scenario-based planning for carbon neutrality and the expasion of natural infrastructure. Khan and Pinter (2016) demonstrated that building density and vegetation cover are critical determinants of carbon emissions, highlighting the role of spatial planning. Similarly, Wang et al. (2021a), using an NSGA-II model with random forests and regression trees, confirmed that areas with higher vegetation and lower building density are most effective at reducing emissions while meeting urban population needs.

Cross-sector innovations also contribute to decarbonization strategies. Giudicianni (2023) emphasized the potential of energy recovery in water distribution networks to decrease greenhouse gas emissions and increase utilities' energy autonomy. However, Crosson et al. (2024) noted that water scarcity and unequal access remain pressing global concerns, particularly in growing urban areas. In this context, hydropower plants with energy recovery stations can help utilities move toward net-zero goals, especially when combined with renewable sources such as solar and wind (Giudicianni, 2023). For off-grid regions, hybrid systems powered by helium, hydrogen, and natural gas—as developed by Greenvale Energy in Australia—offer alternative solutions (Crosson et al., 2024).

Ensuring urban sustainability within interconnected systems demands integrated ecological resource management, guided by the FEW nexus. Zhang et al. (2019), Krueger et al. (2022), Meng et al. (2022), and Zhuang et al. (2022) advocate for scenario-based analyses to assess urban FEW demands. Using an environmentally extended multi-scale input–output model (EE-MSIO), Meng et al. (2022) analyzed resource flows in four Chinese megacities—Beijing, Shanghai, Tianjin, and Chongqing—and found an overwhelming dependence on external inputs: 72–77% of energy, 87–92% of water, and 95–99% of land.

In Africa, cities in the Zambezi and Niger River basins present considerable potential in agriculture, hydropower, biodiversity, and tourism. Nonetheless, challenges such as water scarcity, oil pollution, and food insecurity persist due to unsustainable resource exploitation. Muhirwa et al. (2023) and Apeh and Nwulu (2024) argue that the Food-Energy-Water-Ecosystem (FEWE) nexus offers a comprehensive approach for optimizing the metabolic relationships among ecological, demographic, and social components.

Effective public policy and sectoral planning require intersectoral integration. However, such integration is often deficient. In an evaluation of Brazilian policy frameworks, Souza and Versieux (2021) found that while the water sector demonstrated the most advanced integration, agriculture showed only fragmented efforts,

and the energy sector lagged significantly. This lack of coordination poses a significant barrier to sustainable and coherent development strategies.

In the pursuit of integrated resource management and informed decision-making, various modeling tools simulate FEW system dynamics and explore future scenarios. Among these, the Multi-Scale Integrated Assessment of Society and Ecosystem Metabolism (MuSIASEM), Open-Source Energy Modeling System (OSeMOSYS), Soil and Water Assessment Tool (SWAT), Environmental Policy Integrated Climate (EPIC), Long-range Energy Alternatives Planning (LEAP), and GEM-E3 are prominent frameworks for evaluating sustainability strategies.

The MuSIASEM model, as emphasized by Apeh and Nwulu (2024), enables multi-scalar and regional analysis of FEW flows by integrating demographic, climatic, and economic variables. This integration facilitates the evaluation of policy feasibility and supports more adaptive and realistic resource governance. According to Giampietro (2023), MuSIASEM offers both diagnostic and anticipatory capabilities, aiding in identifying sustainability constraints and detecting implausible policy assumptions.

Table 17.3 shows the main challenges and opportunities to consider when implementing FEW Nexus toward net-zero emissions.

Within the CLEWs framework (Climate, Land, Energy, and Water systems), the OSeMOSYS platform enables long-term linear energy system optimization across diverse spatial and socioeconomic settings. Ramos et al. (2022) note that OSeMOSYS is cost-free, community-driven, and highly adaptable to localized data inputs. By incorporating quantitative indicators such as precipitation levels, energy

Table 17.3 Opportunities and challenges of net-zero emissions faced by FEW nexus

Opportunities	Challenges
Ecosystem restoration and nutrient and water retention in soils to improve adaptive capacity and resilience to climate change in indigenous communities (Gomez et al., 2022) Ecosystem restoration, afforestation, and reforestation using biopesticides (bioeconomy innovation) (Gomez et al., 2022) Regulatory adaptation (Tait et al., 2023) Fostering of local employment opportunities and other social benefits from CBE and LE projects (Xiu et al., 2023) Potential to increase energy infrastructure capacity by tapping into local carbon sinks rather than fossil fuel-based infrastructure (Xiu et al., 2023) Electrical grid integrated with transport infrastructure and vehicles through the concept of smart cities (Arent et al., 2022	Adaptation of CBE and LE practices to local conditions, ensuring availability of energy and resources, industrial structure, and economic development (Xiu et al., 2023) Economic risks and costs associated with innovative technologies and patterns (Xiu et al., 2023) Existence of research on decision-making in the technical-political sphere with no popular/family participation (Hsu et al., 2022) Possibility of social barriers in the implementation of LE and CBE-based projects (Xiu et al., 2023) Lack of measurement of emissions by most cities due to the difficulty of accurate measurement (Hsu et al., 2022) Difficulty for cities to achieve net-zero alone, due to their social and natural particularities, indicating the need for local-regional cooperation (Hsu et al., 2022)

demands, and agricultural yields, the model uncovers trade-offs and synergies among interdependent systems to guide sustainable development strategies.

The SWAT model (2024), developed in the United States, is widely employed to evaluate land and water use practices at the watershed level. It simulates hydrological and biogeochemical processes, including water flow, sediment transport, and agrochemical dynamics. SWAT also accounts for the effects of land use changes, climate variability, and population pressures. Its extended version, SWAT+, is enhanced by geospatial tools such as QGIS, Python, and R, broadening its global applicability. Bailey et al. (2020) demonstrated the effectiveness of the Gwflow module in SWAT+ for simulating both surface and subsurface hydrology in the Little River Experimental Basin, supporting integrated conservation and water resource planning.

The transition toward sustainable systems is increasingly facilitated by the integration of Artificial Intelligence (AI) techniques, including machine learning, neural networks, and genetic algorithms. These technologies contribute significantly to improving energy efficiency, forecasting carbon emissions, and enhancing decision-making processes in construction and land use planning (Li et al., 2024).

Figure 17.6 highlights the aspects involved in decision-making when it comes to urban land use planning, through the existence of public policies, environmental restrictions, established objectives, and technological support for local or regional decisions.

The transition toward sustainable systems is increasingly facilitated by the integration of Artificial Intelligence (AI) techniques, including machine learning, neural networks, and genetic algorithms. These technologies contribute significantly to improving energy efficiency, forecasting carbon emissions, and enhancing decision-making processes in construction and land use planning (Li et al., 2024).

Advanced modeling tools further support this transition. The Environmental Policy Integrated Climate (EPIC) model, developed by Texas A&M AgriLife Research (2024), simulates agricultural processes such as plant growth, water

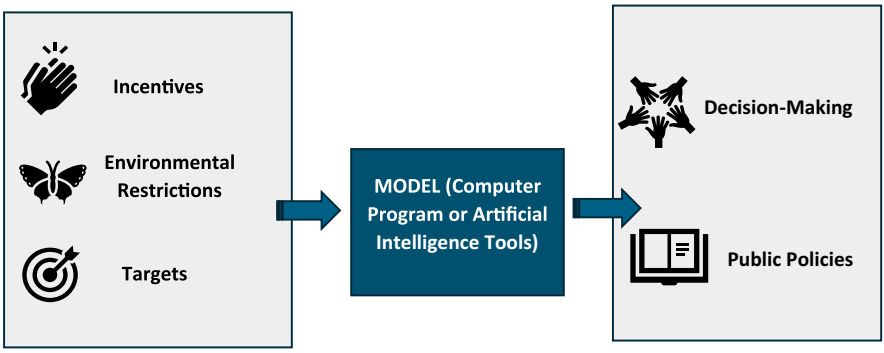

Fig. 17.6 Relevant aspects for decision-making by land use analysis models aiming at the net-zero emissions

consumption, nutrient cycling, erosion, and carbon/nitrogen fluxes. Supporting approximately 80 crop types under various climatic and management scenarios, EPIC is applicable to both local and regional scales. Similarly, the Long-range Energy Alternatives Planning (LEAP) system, from the Stockholm Environment Institute (2024), models energy systems with a focus on climate mitigation by integrating energy, water, and food sector dynamics. LEAP also enables real-time analysis to inform resilient, low-carbon policy strategies.

The Integrated Model to Assess the Global Environment (IMAGE), developed by the PBL Netherlands Environmental Assessment Agency (2024), incorporates subsystems such as TIMER, Land Use Scanner, and GLOBIOM to assess the environmental consequences of human activity. It provides a systems-based perspective on land use, energy, climate, and sustainability policy. Complementing this, GEM-E3—a general equilibrium model by E3 Modelling (2024)—integrates economic, energy, and environmental (E3) dimensions to evaluate the effects of low-carbon policies on emissions, energy consumption, and economic growth within the Energy–Economy–Environment Nexus.

These integrated management models are critical for analyzing FEW Nexus dynamics under climate and socioeconomic pressures. In the Mekong River Delta, Wang et al. (2021b) applied a comprehensive modeling framework to assess combined impacts on rice production, energy generation, and water use. Their findings indicate that while energy production may increase with development, rice yields are at risk from extreme weather, and water demand could increase by 40% by 2050 relative to 2016, underscoring water's pivotal role in linking food and energy systems.

Land use and cover are also decisive factors in terrestrial carbon cycles. In northwest China, Chen et al. (2023) employed a multi-objective optimization model integrating InVEST, IPCC methodologies, NSGA-II, and PLUS tools to analyze various land use scenarios—natural development (ND), low-carbon emissions (CE), high carbon storage (CS), and carbon neutrality (CN). Their results revealed that the expansion of built-up and agricultural lands between 2000 and 2020 led to higher carbon emissions and a decline in forest and water areas.

Broadly, environmental responses to anthropogenic inputs vary spatially. Song et al. (2019), synthesizing 1119 experiments, demonstrated that elevated temperatures, CO_2 enrichment, and nitrogen inputs accelerate the carbon cycle, whereas reduced rainfall has a dampening effect. These impacts are modulated by latitude and topographic variation, as further discussed by Liu and Nie (2020).

Supporting low-carbon urban development, Liu et al. (2022) used the NSGA-II model in Changxing, China, to optimize land-use based on economic, environmental, and spatial accessibility metrics. Their results suggest that rational land-use planning improves soil quality, reduces emissions, and enhances spatial configuration. Complementarily, Li et al. (2023) highlighted the potential of carbon storage to offset ecological losses from land conversion and maintain ecosystem functionality.

17.6 Conclusion and Futures Directions

Climate change has driven the development of new strategies for managing natural resource exploitation, particularly in countries with high levels of greenhouse gas (GHG) emissions. The global race toward carbon neutrality has prompted urgent initiatives to meet this critical milestone. Learning from successful experiences can enhance preparedness for climate change, strengthen natural resource governance, and support progress toward the Sustainable Development Goals (SDGs).

Control and monitoring mechanisms for rational land use have advanced the integration of precision technologies, computational modeling, and scenario forecasting—contributing to assessments of land use impacts on global warming. The interactions among society, the economy, and the biosphere are becoming increasingly complex and interdependent, especially within the context of the FEW nexus.

International policy implementation and the promotion of advanced technologies have fostered entrepreneurship in critical areas: reducing food waste through local consumer–producer chains; transforming solid waste into biomass for energy production; reusing water for secondary purposes; reducing losses in water systems; and improving energy distribution infrastructure and affordability.

Nonetheless, global climate decisions can impact economic development and may exacerbate social short-term vulnerabilities leading populations to settle in environmentally and socially fragile areas with limited access to infrastructure. In this context, local governments that encourage and disseminate cost-effective technologies play a pivotal role in anticipating future resource demands. Urban strategies focused on carbon reduction, sequestration, or neutrality—through the adoption of low-emission renewable energy and socially inclusive environmental policies—can foster resilient cities and healthier populations.

Experiences from various countries demonstrate diverse pathways for the diffusion of sustainable technologies. Promoting local food systems contributes to food security and reduces financial losses. Access to safe water ensures public health, while universal electricity access supports social justice and social equity.

Cooperation between nations and across levels of governance is essential for implementing context-specific and effective measures to achieve net-zero carbon emissions. Cities—being consumption hubs and generators of intersectoral energy flows—require targeted research to explore the intersection of the circular bioeconomy and the FEW nexus in advancing urban sustainability.

Ultimately, transitioning food and water production systems toward integration with renewable energy requires the development of land-use control systems supported by financial instruments and digital platforms that promote public engagement and sustainable behavioral shifts. Bioeconomy-driven projects that move beyond business-as-usual models are indispensable for the near future, particularly when they integrate socioeconomic, climatic, and urban considerations.

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Chapter 18
Impact of Progress of AI on Circular Bioeconomy: Applications, Challenges, and Future Directions

Charles Cao, Jie Zhuang, Jie Jayne Wu, and Wenjun Zhou

18.1 Introduction

18.1.1 Circular Bioeconomy (CBE): Principles, Scope, and Imperatives

The global economy faces unprecedented pressure from climate change, resource depletion, biodiversity loss, and environmental degradation, largely driven by the prevailing linear economic model of "take-make-dispose" (Zocco & Malvezzi, 2024; Ali, 2023). This extractive system, heavily reliant on finite fossil resources, generates vast amounts of waste and greenhouse gas emissions, exceeding planetary boundaries and threatening future prosperity. In response, the concept of CBE has emerged as a transformative strategy for sustainable development, integrating the principles of the bioeconomy with those of the circular economy (Holden et al., 2022; Holden, 2022).

Defining CBE CBE represents a convergence of two powerful concepts. The bioeconomy encompasses economic activity derived from the sustainable use of renewable biological resources—such as plants, animals, microorganisms, and derived

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biomass including organic waste—to produce food, feed, energy, materials, chemicals, and other value-added products (McCormick & Kautto, 2013; Gawel et al., 2018). It spans multiple sectors, including agriculture, forestry, fisheries, aquaculture, food processing, textiles, construction, chemicals, and energy. The circular economy, in contrast, aims to decouple economic activity from the consumption of finite resources by designing out waste and pollution, keeping products and materials in use at their highest value for as long as possible, and regenerating natural systems.

Formally, we consider that CBE is defined as an economic system emphasizing the sustainable, resource-efficient, and cascading valorization of renewable biological resources and waste streams within closed-loop systems (Rojas-Serrano et al., 2024; Guldemund & Zeller, 2024). It seeks to maximize the value extracted from biomass over its lifecycle, minimize waste generation, reduce reliance on fossil inputs, and actively restore natural capital. This involves not merely substituting biological resources for fossil ones, but fundamentally redesigning production and consumption patterns based on circular principles. This systemic shift moves away from linear value chains toward integrated, multi-output production systems, exemplified by biorefineries that utilize residues and biowastes, thereby optimizing resource flows and minimizing environmental impact (Ulfbeck, 2022; Murtz & Palkovits, 2024).

Figure 18.1 illustrates the interconnected processes within CBE, showing how renewable biomass sources flow through sustainable harvesting, processing, and production stages before entering consumer use. The cycle continues through waste collection and preprocessing, leading to biochemical conversion and organic nutrient recycling, which ultimately contributes to ecosystem regeneration and renewed biomass sources.

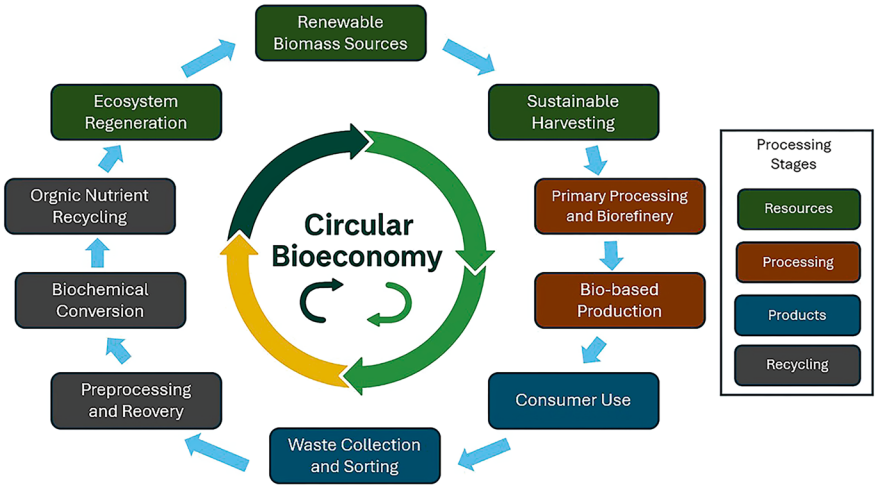

Fig. 18.1 CBE framework: Key processes and interconnections in resource flow

Core Principles CBE operates on several interconnected key principles crucial for its success. A foundational principle is *Sustainable Sourcing*, which mandates the utilization of renewable biological resources (biomass) from diverse sources in a manner that ensures regeneration and avoids the depletion of natural capital. Complementing this is the imperative of *Designing Out Waste and Pollution*, applying circular design principles to bio-based products and processes to minimize waste generation throughout their entire lifecycle. Furthermore, CBE emphasizes *Keeping Products and Materials in Use* at their highest possible value for as long as possible. This is achieved through strategies like extending product lifetimes, reuse, repair, remanufacturing, and recycling, often guided by the waste hierarchy where energy recovery is considered a less preferred option. This encompasses the concept of cascading use, where biomass is sequentially utilized for higher-value material applications before potentially being used for energy. Moving beyond merely minimizing harm, the principle of *Regenerating Natural Systems* advocates for practices that actively enhance ecosystem health, biodiversity, and soil fertility, aiming to restore natural capital (Yanfika et al., 2024; Muscat, de Olde, et al. 2021). Finally, *Optimizing Value Over Time* is achieved by employing integrated systems, such as biorefineries, to extract the maximum potential value from biomass feedstocks, including co-products and residues, thereby improving overall resource efficiency.

The Imperative for CBE The transition to a CBE is increasingly viewed as essential for addressing multiple interconnected global challenges. It offers pathways to mitigate climate change by replacing fossil fuels and carbon-intensive materials with renewable, bio-based alternatives, and enhancing carbon sequestration in soils and products. It tackles resource depletion by shifting reliance to renewable feedstocks and maximizing resource efficiency through circularity. CBE strategies can help preserve biodiversity and reduce environmental pollution by promoting sustainable land management practices and utilizing waste streams. Furthermore, it contributes to food security by optimizing agricultural resource use and converting food waste into valuable resources like biofertilizers or feed (Olesen et al., 2023; Smith et al., 2020). CBE aligns strongly with the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production), but also significantly contributes to goals related to climate action (SDG 13), life below water (SDG 14), life on land (SDG 15), and others. Beyond environmental and social benefits, CBE presents significant economic opportunities, with potential market value estimates reaching billions of USD, driven largely by growth in non-food biobased products such as pharmaceuticals, advanced textiles, innovative building materials, and sustainable packaging (Yuniati et al., 2024; Behera et al., 2022).

Complexity and Challenges Despite the promise of CBE, realizing its potential faces considerable hurdles. CBE systems are inherently complex, involving the management of highly interconnected and dynamic biological resources, diverse and variable feedstocks, intricate multi-actor supply chains, complex waste valorization processes, and crucial ecosystem interactions. Key challenges include

ensuring policy coherence across multiple sectors (e.g., agriculture, energy, environment, industry), which often operate in silos (Muscat, Olde, et al., 2021; Christensen et al., 2022), overcoming the significant inertia of existing fossil-based production systems and infrastructures, scaling up innovative bio-based solutions to be economically competitive, addressing key knowledge gaps including data availability and a deep understanding of complex biological systems, and managing potential trade-offs, such as the competition for biomass between food, feed, materials, and energy applications. While CBE aims for both economic growth and environmental sustainability, achieving this requires systematic navigation. The pursuit of economic benefits must remain within established planetary boundaries, under strong political vision and effective governance structures to guide priorities and ensure that the bioeconomy transition is genuinely sustainable across environmental, social, and economic dimensions. This inherent complexity and the critical need for sophisticated optimization, prediction, and decision-making capabilities create a compelling case for leveraging advanced analytical and operational tools, particularly those offered by the rapid advancements in Artificial Intelligence (AI).

18.1.2 The Advancement of AI: From Machine Learning to Generative Models and Autonomous Agents

AI is rapidly evolving, offering increasingly sophisticated capabilities with the potential to address the complexities inherent in CBE. While traditional Machine Learning (ML) has already found valuable applications in the bioeconomy—for instance, in predicting crop yields (Morales & Villalobos, 2023; Gul & Banday, 2024), forecasting waste generation patterns (Simranjeet via Analytics Vidhya, 2025), or optimizing specific bioprocess parameters (Khanal et al., 2023)—recent advancements represent a significant leap forward in capability and accessibility. Traditional ML typically involves algorithms learning patterns from historical data to perform specific predictive or classification tasks. The current wave of AI, however, introduces tools with fundamentally new capabilities, spurred significantly by the public release and widespread adoption of tools like ChatGPT since late 2022, which has democratized access to state-of-the-art AI tools.

Generative AI (GenAI) represents a major shift from conventional AI tools. GenAI refers to a class of AI models capable of creating content that mimics the patterns and structures present in the data they were trained on. This generated content can span various modalities, including coherent text, realistic images, audio, video, software code, and even complex structures like novel molecules or protein sequences (Hagos et al., 2024; Linkon et al., 2024). Trained on massive datasets, these models learn underlying patterns and relationships, enabling them to generate novel outputs in response to user prompts or specified constraints. Key capabilities that distinguish GenAI include not only content creation but also sophisticated data analysis for identifying complex patterns, adaptability in refining outputs based on

user feedback, and the potential for personalization, tailoring outputs to individual user needs or specific contexts. The potential impact is vast, with some industry observers suggesting that GenAI could transform any field requiring original human creation, fueling massive investment and rapid development of CBE.

Large Language Models (LLMs) are a prominent and highly influential subset of GenAI, specializing in understanding, processing, and generating human-like text. Built on advanced deep learning architectures, such as the Transformer (Vaswani et al., 2017), and trained on vast corpora of text and code, LLMs exhibit remarkable abilities in natural language processing (NLP). Their capabilities are particularly relevant for the knowledge-intensive CBE domain. These include powerful knowledge synthesis, allowing them to extract, summarize, and integrate information from extensive textual sources like scientific literature, technical reports, and policy documents (Han et al., 2024; Pan et al., 2023). They also excel at complex question answering, providing detailed and context-aware responses based on their training data or retrieved information. Furthermore, their proficiency in translation and summarization facilitates communication across language barriers and helps condense large volumes of information into digestible formats (IBM, 2024). A key technique being developed to enhance the reliability and factual accuracy of LLMs is Retrieval-Augmented Generation (RAG). RAG systems connect LLMs to external, often curated and up-to-date knowledge bases (e.g., specific databases, internal document repositories). Before generating a response, the RAG system retrieves relevant information snippets from these sources, which the LLM then uses to formulate its answer. This approach helps to ground the LLM's output in verified facts, mitigating the risk of "hallucinations"—plausible but incorrect statements—which is a known limitation when LLMs rely solely on their internal training data (Lewis et al., 2020; Amazon Web Services [AWS], 2025; Databricks, 2025).

AI Agents (or Agentic AI) represent a further step toward autonomous and goal-oriented systems. These are intelligent software entities designed to perceive their environment (which could be digital or connected to the physical world via sensors), reason about situations, make decisions, formulate plans, and take actions to achieve specific, often complex, goals (Wang, Ma, et al., 2024; Xi et al., 2023). Many contemporary AI agents leverage LLMs as their core reasoning engine, enabling them to understand instructions, decompose problems, and plan sequences of actions. Agents distinguish themselves through their ability to interact dynamically with their environment, utilize external tools (such as calling software APIs, querying databases, running simulations, or invoking other AI models), manage memory and maintain context over extended interactions, learn from feedback to improve performance, and potentially collaborate with other AI agents or human users. Unlike generative assistants that primarily react to user prompts, AI agents can proactively execute complex, multi-step tasks on behalf of a user or system (Beck et al., 2022; Tallam, 2025). Their defining characteristics include a degree of autonomy in operation, sophisticated planning and reasoning capabilities, the ability to interact with and use diverse tools, persistent memory and context management, and mechanisms for learning and adaptation over time. However, AI agent development faces significant challenges including coordination in multi-agent

systems (Li et al., 2024), reliability and security concerns (Lumenova AI, 2024; XenonStack, 2025; Narajala & Narayan, 2025), and technical hurdles in tool integration (Oyelabs, 2025; Li et al., 2024).

These advanced AI tools—GenAI, LLMs, and AI Agents—signify a qualitative shift beyond the pattern recognition and prediction capabilities of traditional ML. They introduce powerful elements of creativity (generation), complex multi-step reasoning and planning, natural language interaction at scale, and autonomous action within dynamic environments IBM (2024). This expanded toolkit offers fundamentally new possibilities for tackling the multifaceted challenges inherent in the transition to CBE. It is important to recognize that these technologies often work synergistically; for instance, LLMs provide the cognitive foundation for many AI agents, enabling them to understand instructions, reason for problems, and plan actions, while generative capabilities might be invoked by an agent as part of task execution (e.g., generating a report or designing a component). While the internal workings of large models like LLMs can be highly opaque ("black boxes") (Rudin, 2018), the structured approach often employed by AI agents, involving explicit planning steps and interaction with defined external tools, can offer a degree of process transparency. The agent's intended plan and the sequence of tools it utilizes can often be logged and inspected, providing valuable insights into its operational flow, even if the LLM's internal reasoning remains obscured (Li et al., 2024). This potential for greater process visibility is relevant for validation, debugging, and trust-building in complex applications.

18.1.3 Framing the Intersection: Synergies and Scope of Advanced AI in CBE

The transition to CBE involves managing highly interconnected, dynamic, and data-rich systems, from supply chains and waste valorization processes to ecosystem service flows. Current approaches often struggle with this inherent complexity, hampered by siloed data management, limited integration of insights across disciplines, and the use of relatively static policy tools, all of which constrain scalability and effectiveness. Advanced AI technologies, with their enhanced capabilities for generation, reasoning, interaction, and autonomy, are increasingly recognized as key enablers for overcoming these limitations and significantly accelerating the transition toward a sustainable CBE (Spyridis et al., 2024; Gul & Banday, 2024).

The potential synergies between advanced AI and CBE objectives are compelling. The generative power of AI aligns naturally with the need to design sustainable bio-based products, materials, and resource-efficient processes (Kopˇse Kaljun & Kaljun, 2024; Bos et al., 2024; Luu et al., 2024). The sophisticated simulation and prediction capabilities offered by AI agents and advanced predictive models can help optimize complex CBE systems, anticipate future scenarios under

different conditions (e.g., climate change, market shifts), and evaluate the potential impacts of interventions before implementation (Shah et al., 2025; Solis et al., 2021; Yuksel & Sawaf, 2024). Intelligent automation, driven by AI interacting with sensors and actuators, can enhance the efficiency, resilience, and adaptability of bioprocesses and waste management systems (Janus & Steffan, 2024; Paneru et al., 2024; Devi et al., 2025). Furthermore, the natural language processing power of LLMs offers powerful tools for synthesizing the vast and disparate knowledge base relevant to CBE (spanning scientific literature, patents, regulations, and market data), supporting better-informed decision-making by diverse stakeholders (Zheng et al., 2023; Wang, Huey, et al., 2024; Susnjak et al., 2024). Additionally, AI agents and advanced communication tools can facilitate much-needed collaboration and coordination among the diverse actors within the complex CBE ecosystem, bridging knowledge gaps and aligning actions (Piatti et al., 2024; Larosa et al., 2025).

However, the application of AI within a sustainability framework like CBE is not without inherent tensions and potential pitfalls. While AI is positioned as a powerful tool to achieve environmental goals, the development and deployment of AI systems themselves carry environmental costs. Training largescale AI models, especially LLMs, consumes significant amounts of energy, which often contributes to greenhouse gas emissions, and the lifecycle of AI hardware contributes to electronic waste (Balogun & Ali, 2024; Dokic et al., 2024; Zhang et al., 2024; Ariyanti et al., 2024; Zewe, 2025; The Sustainable Agency, 2024; EY Netherlands, 2024; United Nations Environment Programme [UNEP], 2024; Arboreco, 2025). Moreover, AI applications can introduce or exacerbate socio-economic risks, such as algorithmic bias leading to inequitable outcomes, concerns over data privacy and security, and potential disruptions to labor markets through automation (Ma, 2024; Abràmoff et al., 2023; Angela & Odewuyi, 2024; Soni, 2024; Bahamazava, 2024). Therefore, deploying AI in CBE demands a careful, critical, and responsible approach, ensuring that the solutions developed do not inadvertently undermine the core sustainability and equity objectives they aim to support (Shah et al., 2025; Orejuela-Escobar et al., 2024; Al Hashlamoun et al., 2023; Sheikh et al., 2024). A holistic assessment is required to ensure the net benefits outweigh the costs both environmentally and socially.

This chapter focuses specifically on exploring the potential applications and unique challenges associated with these advanced AI tools—namely, Generative AI, LLMs, and AI Agents—within the specific framework of CBE. It moves beyond discussing already established ML applications (like basic prediction or classification) to examine how these newer, more powerful capabilities can drive innovation, efficiency, and system optimization in CBE. Simultaneously, it critically assesses the specific hurdles, risks, and research gaps that these advanced tools introduce in this context. The subsequent sections will investigate: (2) Potential and Emerging Applications enabled by these technologies, (3) Key Challenges and Research Gaps specific to their use in CBE, and (4) the Future Outlook and Research Agenda at this critical intersection of advanced AI and CBE.

18.2 Potential and Emerging Applications of Advanced AI in CBE

The advanced capabilities of Generative AI, LLMs, and AI Agents open up new frontiers for innovation and optimization within CBE. These tools move beyond traditional data analysis and prediction to enable novel design exploration, complex system understanding and simulation, intelligent automation of processes, comprehensive knowledge management, and enhanced stakeholder engagement and collaboration. Table 18.1 provides a summary overview of major application categories explored in this section.

Table 18.1 Examples of advanced AI applications in CBE

Application Category	Example Use Case	AI Technique Involved	Potential Benefits in CBE
Generative Design & Discovery	Designing novel enzymes for biocatalysis; Generative molecular design of bio-based materials.	Generative models (VAEs, GANs, diffusion models) for proteins/chemicals; Reinforcement learning.	Accelerates discovery of sustainable bio-products (enzymes, polymers) with desired properties, reducing R&D time.
Complex System Simulation & Prediction	Predicting crop yields and soil health; Simulating circular supply chains for optimization.	ML prediction models (NNs, RFs); Digital twins; Agent-based modeling.	Improves foresight: better forecasts, optimized logistics, scenario analysis for circular resource use, aiding proactive decisions.
Intelligent Automation & Control	Smart composting or biogas reactors with AI-regulated conditions; Precision agriculture robots/ drones.	Sensor networks/IoT with AI controllers (ANN/SVM); Computer vision; Reinforcement learning agents.	Enhances process efficiency/ stability (e.g., maintaining compost moisture), reduces waste/energy, automates tasks, adapts to dynamics.
Knowledge Synthesis & Decision Support	AI assistant summarizing best practices for farmers/ policymakers; LLM analysis of biomass literature.	LLMs (GPT-3/4+) for text analysis/ generation; Knowledge graphs; Q&A systems.	Condenses vast information into accessible insights (e.g., technical reports into simple guidance), supports evidence-based decisions, reduces information overload.
Enhanced Stakeholder Interaction & Collaboration	Agricultural extension; AI-facilitated workshops.	LLM-based conversational agents; Voice interfaces; Collaborative simulation platforms.	Bridges communication gaps (language, expertise), personalizes services, engages non-experts, fosters knowledge-sharing.

18.2.1 Generative Design and Discovery: Novel Bio-products, Materials, and Processes

One of the most significant potential impacts of advanced AI, particularly GenAI, lies in its capacity to fundamentally accelerate the design and discovery of novel biological solutions tailored specifically to the requirements of CBE. Traditional methods for developing new bio-based materials or biocatalysts often rely on laborious screening of existing compounds or incremental modification of known structures through techniques like directed evolution, which can be slow, costly, and may only explore a limited portion of the potential solution space (Braun et al., 2023; Xie & Warshel, 2023). In contrast, GenAI algorithms can computationally explore vast chemical and biological design spaces to propose entirely new entities—molecules, proteins, microbial strains, or even process configurations—possessing desired functionalities relevant to circularity and sustainability (Liu et al., 2024; Yousefi & Wnek, 2025). This capability is crucial for developing truly innovative materials, highly efficient catalysts, and optimized microorganisms needed to make CBE environmentally effective and economically competitive.

There are several specific application areas that are rapidly emerging, as follows.

- Novel Material Design: GenAI algorithms, trained on datasets of known materials and their properties, can be tasked with designing new bio-based polymers, composites, or other materials with specific characteristics. This could involve designing bioplastics with enhanced biodegradability under specific environmental conditions (e.g., marine or soil), creating high-performance biocomposites derived from waste biomass streams (like agricultural residues), developing materials with improved recyclability profiles, or designing materials with specific functional properties (e.g., barrier properties, hydrophobicity, fire resistance) intended to replace conventional, less sustainable options (Liu et al., 2024; Yousefi & Wnek, 2025). For instance, GenAI could assist in designing biodegradable packaging materials derived directly from locally abundant agricultural or food processing waste, simultaneously addressing waste valorization and plastic pollution challenges (Yousefi & Wnek, 2025).
- Enzyme and Protein Engineering: Where biocatalysis plays a central role in many CBE processes (e.g., biomass conversion in biorefineries, enzymatic recycling of plastics, waste degradation), GenAI can dramatically accelerate the discovery and optimization cycle. By leveraging models capable of predicting protein structures (like AlphaFold) and generating novel sequences, GenAI can design enzymes with enhanced stability under harsh industrial conditions, improved specific activity toward target substrates (such as recalcitrant lignocellulose), or tailored performance characteristics (Braun et al., 2023; Xie & Warshel, 2023). This represents a significant leap from simply predicting properties of existing enzymes to generating blueprints for entirely new biocatalysts designed for a purpose. Advanced protein generative models are making these

capabilities more accessible, aiming to help industries develop more sustainable biocatalysts (Chu et al., 2024).

- Microbial Strain Design: Microorganisms are workhorses in fermentation, waste treatment, biofuel production, and biofertilizer development. GenAI can aid in the computational design of synthetic microbial consortia or the targeted engineering of individual microbial strains. This involves optimizing metabolic pathways for specific CBE tasks, such as efficiently converting complex organic waste streams into valuable platform chemicals or biofuels, enhancing the recovery of nutrients like phosphorus or nitrogen from wastewater, or developing microbes that can thrive on challenging feedstocks.

In general, the transformative power of GenAI in this domain is often realized when it is integrated within a larger innovation ecosystem. Coupling generative design algorithms with sophisticated simulation tools allows for rapid prediction of the performance of designed entities before physical synthesis. Furthermore, integration with automated laboratory platforms ("robot scientists" or "bio-foundries") enables high-throughput synthesis and experimental validation of AI-generated designs (Future Today Institute, 2024). This creates a tightly integrated, closed loop, capable of significantly accelerating the innovation cycle for sustainable biosolutions. A key advantage offered by GenAI is its potential for generating bespoke solutions—materials optimized for specific regional feedstocks, enzymes tailored for unique industrial process conditions, or microbes designed for targeted waste streams (Marquez et al., 2023). This customization potential could dramatically accelerate the development and deployment of effective and economically viable CBE technologies, overcoming limitations associated with adapting generic or off-the-shelf solutions to diverse local contexts and requirements inherent in a global bioeconomy. Table 18.2 provides illustrative examples of how GenAI could be applied.

While acknowledging that many generative applications in CBE are still in the early stages of development or validation (Masudah & Livotov, 2024; Larosa et al., 2025), the potential to rapidly discover and tailor bio-based solutions makes GenAI a cornerstone technology for future CBE innovation. These applications extend beyond physical design to include information processing (Sun et al., 2024; Polignano et al., 2022), which is critical for monitoring sustainability metrics and ensuring compliance with evolving regulations.

18.2.2 Complex System Simulation and Prediction in Bioeconomy

CBE inherently operates as a complex adaptive system, characterized by intricate interactions between biological resources, technological processes, dynamic supply chains, fluctuating market forces, environmental factors, and societal actors (Olesen et al., 2023; Freire et al., 2023). Understanding, predicting, and managing this

Table 18.2 Illustrative examples of generative AI applications in CBE design and discovery

Application Area	Specific Goal Example	Potential GenAI Technique	Relevant CBE Principle
Biopolymer Design	Design polymer with enhanced Biodegradability in marine environments	Molecule Generation Models (e.g., GANs, VAEs, Diffusion Models)	Design for Circularity, Waste Prevention
Biopolymer Design	Develop biocomposite with improved barrier properties using waste lignin	Material Informatics, Structure-Property Prediction Models	Waste Valorization, Resource Efficiency
Enzyme Engineering	Increase catalytic efficiency for lignocellulose breakdown in biorefining	Protein Structure Prediction & Design Models (e.g., AlphaFold-like, RFdiffusion)	Biomass Valorization, Biofuel Production
Enzyme Engineering	Design a novel biocatalyst for degrading specific plastic waste (e.g., PET)	Generative Protein Sequence Models, Active Site Design	Waste Valorization, Pollution Reduction
Microbial Strain Design	Optimize microbial production of Volatile Fatty Acids (VFAs) from food waste	Metabolic Pathway Modeling & Synthetic Circuit Design Tools	Waste Valorization, Biobased Chemicals
Microbial Strain Design	Engineer microbes for enhanced phosphorus recovery in wastewater treatment	Genome-Scale Modeling & Strain Optimization Algorithms	Nutrient Cycling, Resource Recovery
Process Design	Propose a novel bioreactor design optimized for solid-state fermentation of agricultural residues	Process Simulation combined with Generative Design Optimization	Resource Efficiency, Process Intensification

complexity is crucial for the effective implementation, optimization, and scaling of CBE initiatives. Advanced AI, encompassing sophisticated predictive models, physics-informed machine learning, digital twins, and AI agent-based simulations, offers powerful tools for modeling these systems, predicting their behavior under various conditions, and evaluating the potential impacts of different strategies or interventions before they are deployed in the real world (Belvederesi et al., 2020; Zimmermann et al., 2024). Specifically, we identify the following key application areas:

- Supply Chain Simulation and Optimization: CBE involves managing complex logistical networks for sourcing diverse and often variable biomass feedstocks, transporting them efficiently to processing facilities (like biorefineries) and distributing the resulting bio-based products to markets. AI models and agent-based simulations can create detailed virtual representations of these networks (Gómez-Cruz et al., 2017; Holman, 2015). These simulations can incorporate critical factors such as feedstock availability and quality variability (e.g., due to weather or seasonality), transportation logistics costs, storage requirements and degradation risks, processing plant capacities, fluctuations in market demand, and associated environmental footprints (including transport emissions, energy consumption, and potential land use change impacts). AI agents can be programmed to simulate

the decision-making processes of different actors within the supply chain—for instance, farmers choosing which crops to plant based on predicted prices or incentives, logistics providers optimizing delivery routes, or biorefineries managing feedstock inventory based on processing needs and market signals. Analyzing the emergent behavior of these simulated systems allows stakeholders to identify potential bottlenecks, uncover opportunities for optimization (e.g., optimal facility location, inventory strategies), design more resilient logistics networks, and assess the regional impacts of biomass utilization on related sectors, such as food production or water availability.

- Biorefinery and Bioprocess Modeling: Digital twins, which are virtual replicas of physical assets or processes enhanced with AI and ML algorithms, are increasingly used (Hu et al., 2021). These digital twins can simulate complex biochemical and thermochemical conversion processes occurring within bioreactors or downstream processing units. They can predict the yields of multiple products based on varying inputs and dynamically adjusted process parameters, optimize energy integration within the plant to minimize consumption, forecast equipment maintenance needs to prevent downtime, and allow for virtual experimentation to test new process configurations or control strategies without disrupting physical operations (Tamaian, 2023). Hybrid models that combine mechanistic understanding (e.g., biochemical reaction kinetics) with machine learning's ability to learn from data are proving particularly effective in handling the complexity and non-linearities of biological processes (Tsui et al., 2023; Subha et al., 2024).
- Waste Management System Dynamics: Managing organic and other waste streams efficiently is fundamental to closing loops in CBE. AI models can improve predictions of waste generation rates and composition based on demographic data, economic activity, and seasonal factors (Samadhiya et al., 2025). Agent-based simulations and optimization algorithms can evaluate the efficiency, cost-effectiveness, and environmental impact of different waste collection logistics strategies, advanced sorting technologies (including AI powered robotic sorting), and various valorization pathways such as anaerobic digestion, composting, pyrolysis, or insect farming (MacArthur, 2019; Iragavarapu et al., 2023). These simulation capabilities support the design of optimized, integrated waste management infrastructure that maximizes resource recovery and minimizes landfill dependence, contributing directly to circularity goals (Mesa et al., 2024).
- Ecosystem and Environmental Impact. CBE activities, such as large-scale biomass harvesting or the introduction of novel bio-based products, inevitably interact with natural ecosystems. AI-powered ecological models can help simulate the potential impacts of these activities on biodiversity, soil health, water resources, and carbon cycles. They can also be used to assess the potential effects of new bio-based products, such as biodegradable materials, when released into different environmental compartments (soil, water) (Mesa et al., 2024). This predictive capability supports more informed decision-making that effectively balances bioeconomic development objectives with crucial environmental protection goals.

- Market and Policy Scenario Analysis. LLMs can analyze vast amounts of qualitative data, such as news articles, policy documents, social media sentiment, and consumer reviews, to identify emerging trends or concerns related to bio-based products. AI agents can be used to simulate the behavior of market actors (consumers, investors, competing firms) in response to new products or policy changes. This allows for predicting market adoption trends for novel bio-based offerings, assessing the potential economic consequences of different CBE policies or incentive structures (e.g., carbon taxes, subsidies for bio-based materials), and understanding how consumer behavior might influence the speed and direction of the transition toward a CBE. Such "digital scenario planning" provides policymakers with valuable foresight (De Clercq et al., 2024).

A key strength of advanced AI in simulation and prediction for CBE is its potential to bridge different scales (from molecular interactions within a bioreactor to regional supply chains) and disciplines (integrating biological, chemical, economic, ecological, and engineering models). By handling diverse data types (numerical sensor data, textual reports, satellite imagery, market statistics) and modeling the intricate interactions and feedback loops between various system components, AI simulations can provide a more holistic, system-level understanding. This integrated perspective is essential for effectively navigating the complexities, uncertainties, and inherent trade-offs involved in steering the transition toward a sustainable CBE.

18.2.3 Intelligent Automation Control in Processes

The efficient, reliable, and resource-optimal operation of many CBE processes often requires precise, real-time monitoring and control. This is particularly true given the inherent variability associated with biological feedstocks (e.g., differing moisture content, composition) and the dynamic nature of biological processes (e.g., microbial growth kinetics). Advanced AI, when integrated with sensor networks, robotics, and control systems—often encapsulated within concepts like Industry 4.0 or smart manufacturing—enables a significant shift toward intelligent automation and adaptive process control. This integration promises enhanced operational efficiency, improved product quality and consistency, reduced consumption of resources like energy and water, minimized waste generation, and a reduction in the potential for human error in complex operations. Specifically, we identify the following key applications of AI in CBE processes:

- In Smart Biorefineries and Bioprocessing, AI algorithms, particularly ML models (like neural networks or reinforcement learning) and potentially agent-based control systems, are increasingly employed. These systems analyze real-time data streams from various in-situ sensors (such as spectroscopic probes like Near-Infrared/Mid-Infrared (NIR/MIR), temperature sensors, pressure sensors, pH probes, and dissolved oxygen sensors) located within bioreactors or downstream processing units. Based on this continuous analysis, the AI can

dynamically adjust critical process parameters—for example, nutrient feed rates in fermentation, temperature profiles in composting, mixing speeds, or optimal harvesting times—to maintain desired conditions, maximize the yield of target products, ensure consistent product quality, and improve overall resource efficiency (Khanal et al., 2023; Isoko et al., 2024). Digital twins often serve as a core component in these systems, providing the virtual model necessary for simulation, prediction, and optimization of control loops before implementation on the physical system. ML techniques like Artificial Neural Networks (ANN) and Support Vector Machines (SVM) have demonstrated success in modeling and optimizing complex bioprocesses, often outperforming traditional control methods in handling non-linearities and variability. For example, ML models have been used to predict and prevent instability (e.g., ammonia accumulation) in anaerobic digesters (Tsui et al., 2023).

- In the crucial area of resource recovery, Automated Waste Sorting and Handling benefits significantly from AI. Recovering high-quality secondary raw materials from mixed waste streams is fundamental to circularity. AI-powered robotic systems, equipped with computer vision and other sensors (e.g., hyperspectral imaging, tactile sensors), can automate the sorting of complex waste streams, such as mixed plastics, construction and demolition waste, or electronic waste that might contain bio-based components (Sousa et al., 2019; Lubongo et al., 2024). These intelligent systems can identify and segregate different materials with higher speed, accuracy, and consistency than manual sorting, thereby enabling the recovery of cleaner material fractions suitable for high-value recycling or upcycling into new products (Sayem et al., 2025; Cheng et al., 2024).
- Sustainable sourcing of biomass, a cornerstone of CBE, is enhanced through Precision Agriculture and Forestry for CBE Feedstocks. AI algorithms analyze data collected from various sources, including ground-based sensors, drone-mounted cameras (multispectral, thermal), and satellite imagery, to enable highly targeted management techniques specifically geared toward producing CBE feedstocks sustainably (Segar et al., 2024; Mudrak & Morozova, 2023). This includes optimizing the application of inputs like water and bio-based fertilizers or pest controls only where and when needed, predicting optimal harvest times to achieve specific biomass quality attributes desired by downstream processors (e.g., lignin content for biorefining), and continuously monitoring crop or forest health to maximize sustainable yields while minimizing negative environmental impacts such as nutrient runoff or soil degradation (Södergård, 2021; Ramos-Maldonado et al., 2025).
- Looking further ahead, AI agents hold the potential for Autonomous Operations and Coordination of entire segments within a CBE facility, such as managing a complete biorefinery production line or coordinating operations in a waste processing plant. These sophisticated agents could orchestrate the actions of multiple automated systems (robots, control valves, conveyors), monitor overall system performance against key indicators, predict potential equipment failures or process deviations using predictive maintenance algorithms, and autonomously respond to unexpected events (e.g., a sudden change in feedstock quality)

or shifting conditions (e.g., changes in energy prices or product demand), thereby optimizing operations with significantly reduced need for constant human intervention (Sivakumar, 2024; Simion et al., 2024). The concept of the "self-driving lab" or automated bio-factory, where AI guides robotic experimentation to rapidly optimize strains or processes, represents an early example of this trend toward autonomous R&D and potentially production (Chen, Zhu, et al. 2024; Prabu et al., 2025).

Overall, intelligent automation driven by AI not only improves efficiency in existing, often centralized, facilities but also potentially enables the development of more distributed and adaptive CBE infrastructure. AI-controlled systems could make smaller-scale, modular biorefineries or waste valorization units economically and operationally feasible (Rivas-Interian et al., 2022; Alamia et al., 2017). Such units could be located closer to distributed feedstock sources (e.g., farms, small communities, food processing clusters) or end-users, thereby reducing transportation costs and logistical complexity. Furthermore, AI allows these distributed units to adapt their operations dynamically based on local factors like feedstock availability and quality variations, prevailing energy costs, and real-time market demands for their output products, enhancing overall system resilience and supporting the development of robust regional circular bio-economies (Turner et al., 2021; Ramirez-Corredores et al., 2020).

18.2.4 Knowledge Synthesis and Decision Support

CBE is an inherently knowledge-intensive field, drawing upon and integrating insights from diverse disciplines. The sheer volume, complexity, and distributed nature of relevant information—spanning peer-reviewed scientific literature, patents, technical reports, market data, governmental regulations, policy documents, and even local or indigenous knowledge—pose a significant challenge for researchers, policymakers, industry practitioners, farmers, and other stakeholders to stay informed and make evidence-based decisions. Advanced AI, particularly LLMs and specialized AI agents, offers powerful capabilities for navigating this complex information landscape, synthesizing disparate knowledge sources, extracting key insights, and providing tailored decision support (Susnjak et al., 2024; Wang, Huey, et al., 2024).

Figure 18.2 illustrates an integrated decision support dashboard that leverages AI and digital twin technology to assist stakeholders in visualizing, analyzing, and optimizing CBE systems. This interactive platform enables users to model different scenarios, track resource flows, and make data-driven decisions by combining geographic information with AI-powered simulation capabilities.

One of the most immediate impacts is on Accelerated Literature Review and Knowledge Synthesis. LLMs can process and analyze scientific papers, patents, technical reports, and news articles on specific CBE topics much faster and more

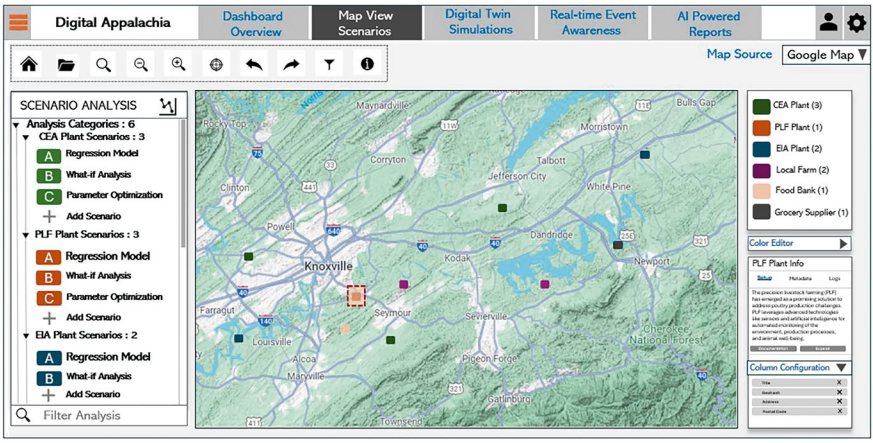

Fig. 18.2 AI-powered digital twin dashboard for CBE decision support: Integrating geographic information systems, scenario analysis, and real-time simulation tools

comprehensively than human researchers typically can. They can automatically generate summaries of key documents, extract specific findings or data points, identify emerging trends or patterns across multiple studies, compare different methodologies and results, and synthesize the current state of knowledge on complex subjects ranging from advanced biofuel conversion technologies to lifecycle environmental impacts of different bioplastics and best practices in sustainable forestry management (Garcia et al., 2024; Susnjak, 2023). This capability drastically reduces the time required for literature reviews and helps researchers stay updated on the latest developments in this rapidly evolving field (Iyer et al., 2024; Iacus et al., 2025).

AI also assists in Policy Analysis and Regulatory Navigation. CBE operates within a complex and often fragmented web of national and international policies, regulations, and standards. LLMs can be trained to assist policymakers and businesses by analyzing lengthy policy documents, identifying relevant regulations applicable across different jurisdictions and sectors, summarizing complex compliance requirements, and potentially even assessing the likely impacts of proposed policies based on available evidence and simulation results. This can improve policy coherence and help stakeholders understand their obligations and opportunities within the regulatory landscape

In the commercial sphere, AI contributes to Market Intelligence and Trend Analysis. AI agents can be programmed to continuously monitor and analyze diverse data streams, including news feeds, market research reports, trade publications, social media discussions, patent filings, and company reports (Olayinka, 2023; Lesmana et al., 2024). This enables providing real-time insights into market trends for specific bio-based products, fluctuations in feedstock prices and availability, competitor strategies, emerging technologies, and evolving consumer preferences and concerns related to sustainability and circularity (Methuku, 2025; Gatto

& Re, 2021). Such intelligence is vital for business planning and investment decisions in the bioeconomy.

Furthermore, AI systems can function as expert assistants for Technical Question Answering and Problem Solving. LLM-based systems, particularly when enhanced with Retrieval-Augmented Generation (RAG) to access specific technical databases, scientific literature repositories, or internal company knowledge bases (Liu et al., 2025; Siriwardhana et al., 2023), can provide engineers, researchers, operators, and farmers with quick, context-aware answers to technical questions (Xu et al., 2024; Gupta et al., 2024). This might relate to specific bioprocess parameters, material properties, equipment operation procedures, safety protocols, environmental regulations, or troubleshooting operational issues.

AI can help organize, curate, tag, and maintain large, dynamic repositories of information relevant to the CBE community, developing and maintaining Shared Knowledge Hubs. This ensures that pertinent research findings, validated best practices, up-to-date market data, regulatory information, and case studies are easily searchable and readily accessible to all stakeholders, fostering a common evidence base and promoting shared understanding across the diverse actors involved (Dieken et al., 2021).

Finally, by systematically analyzing the existing body of literature, AI tools can help with Identifying Research Gaps and Innovation Opportunities (Shi et al., 2023; Randolph et al., 2024). They can highlight underexplored research areas, identify emerging technological trends by tracking keyword frequencies or citation networks, and uncover potential synergies between different fields or technologies within CBE, thereby guiding future research directions and strategic innovation efforts (He et al., 2024; Susnjak et al., 2024).

A crucial aspect of these applications is the potential for LLMs and AI assistants to democratize access to complex knowledge (Fer et al., 2021). CBE often involves highly specialized information that can be inaccessible or difficult to understand for stakeholders without deep technical or scientific expertise, such as smallholder farmers, community organizations, smaller enterprises, or policymakers navigating unfamiliar scientific territory (Gkikas et al., 2023). LLMs excel at translating complex scientific concepts and technical jargon into clearer, more understandable language tailored to different audiences (IBM, 2024). By acting as knowledge translators and providing information in accessible formats through user-friendly interfaces (e.g., chatbots, simplified dashboards, voice interactions), AI can empower a broader range of actors to participate more effectively in CBE-related decision-making, innovation, implementation, and governance. Studies have shown, for example, how LLMs can distill complex agronomic research into practical, actionable advice for farmers in accessible language. However, as noted previously, ensuring the accuracy and contextual relevance of this synthesized knowledge remains a critical challenge, which approaches like RAG help mitigate by grounding responses in verified information sources (Tzachor et al., 2023).

18.2.5 Enhanced Interaction and Collaboration of Stakeholders

Achieving a successful and equitable transition to CBE requires effective communication, coordination, and collaboration among a wide array of diverse stakeholders. These actors include primary producers (farmers, foresters, fishers), industry players (biorefineries, manufacturers, retailers, waste processors), researchers and technology developers, policymakers and regulators at various levels, financial institutions, consumers, non-governmental organizations (NGOs), and local communities impacted by bioeconomy activities. Bridging the significant gaps in understanding, aligning often divergent interests, building trust, and facilitating joint action across these varied groups can be exceptionally challenging due to differences in expertise, language, priorities, and access to information. Advanced AI, leveraging the capabilities of LLMs for communication and AI agents for coordination, offers promising new tools to significantly enhance stakeholder interaction and collaboration within the CBE ecosystem (Fer et al., 2021). Specifically, we identify the following key areas.

- AI-Powered Communication and Translation Platforms. Collaboration platforms incorporating LLMs can effectively overcome communication barriers that often hinder multi-stakeholder initiatives. Potential features include real-time translation capabilities to support international partnerships or engagement with diverse linguistic communities, automated summarization of lengthy meeting transcripts or complex documents to ensure shared understanding among participants with varying levels of engagement or expertise, and AI assistance in drafting clear, concise communications tailored to the specific knowledge level and interests of different stakeholder users (Fer et al., 2021). This can streamline communication flows and reduce misunderstandings.
- Intelligent Matchmaking and Network Building. AI agents could analyze detailed stakeholder profiles, declared interests and needs, available resources (e.g., specific types of biomass availability, existing processing capacity, technological expertise), and specific project requirements to identify and proactively suggest potential partnerships within the CBE value chain (Gkikas et al., 2023). For example, such a system could automatically connect farmers with surplus agricultural residues to nearby biorefineries seeking feedstock, link producers of novel bio-based materials with manufacturers looking for sustainable inputs, or identify research groups possessing complementary expertise for collaborative R&D projects. This facilitates the formation of new value chains and innovation networks.
- Facilitating Consensus Building and Negotiation. LLMs could analyze stakeholder submissions, feedback forms, or discussion transcripts to objectively identify areas of common ground, pinpoint key points of contention, and help

articulate the underlying interests and concerns of different parties. In more advanced scenarios, AI might even be able to suggest potential compromise solutions based on predefined criteria or facilitate structured online dialogues designed to help groups navigate disagreements and move toward consensus (Fer et al., 2021).

- Personalized Information Delivery and Engagement at Scale. E-governance platforms, industry portals, or extension service websites can use AI algorithms to deliver tailored information, relevant alerts (e.g., about new funding opportunities or regulatory changes), and specific engagement opportunities directly to stakeholder groups based on their predefined roles, stated interests, geographical locations, or past interactions (Gkikas et al., 2023). For instance, farmers might receive targeted information about subsidies available for adopting specific sustainable practices relevant to their farm type, while consumers could receive updates on the availability of certified bio-based products in their local retail outlets.

While related to knowledge access, the unique contribution here lies in AI actively *facilitating interaction* and enabling *joint action*, moving beyond simply providing information passively. AI agents, for instance, could potentially serve as neutral digital coordinators or automated project managers for complex, multi-stakeholder CBE initiatives (Wally Boston, 2024). They could manage communication flows between different project partners, track progress against shared goals and milestones, automatically flag potential issues or delays based on incoming data, and even facilitate resource allocation or scheduling based on predefined rules or optimization algorithms. By automating routine coordination tasks and reducing friction in collaboration, AI could significantly improve the efficiency and success rate of complex CBE projects that inherently rely on effective cooperation across diverse organizations and individuals with potentially conflicting schedules or priorities.

18.3 Key Challenges and Research Gaps for AI in CBE

Despite the significant potentials outlined above, the development and deployment of advanced AI (Generative AI, LLMs, AI Agents) within the specific context of CBE faces substantial challenges and reveal critical research gaps. These hurdles span technical issues like data availability and model reliability, practical concerns regarding integration into existing systems, profound ethical considerations unique to the sustainability domain, and the need for adaptive policy and regulatory frameworks. Addressing these multifaceted challenges proactively and rigorously is crucial for realizing the benefits of AI in CBE in a responsible, effective, and equitable manner. Table 18.3 provides a summary of these key challenge areas.

Table 18.3 Key challenges of applying advanced AI in CBE

Challenge Area	Description and Implications
Data Scarcity, Specificity & Quality	Advanced AI models, especially deep learning-based ones like LLMs, are often data hungry. However, many CBE domains suffer from a lack of large, comprehensive, high-resolution, and longitudinal datasets. This is particularly true for detailed biological process data, real-time supply chain dynamics, long-term environmental impacts of CBE practices, or performance data for novel bio-based materials in real-world applications. Generating such data can be costly and time-consuming. Furthermore, CBE data is often highly specific and contextual (e.g., biomass properties vary greatly; process outcomes depend on specific conditions), making it difficult to train generalizable models. Data heterogeneity (diverse formats like sensor readings, text, images) and quality issues (missing values, errors, noise, bias) further complicate AI development. These limitations create a "cold start" problem and hinder the development of robust and reliable AI solutions for CBE.
Validation, Reliability, & Hallucination Risk	Ensuring the trustworthiness, accuracy, and reliability of outputs from advanced AI systems is paramount, especially in high-stakes CBE applications. LLMs are known to "hallucinate," generating plausible but factually incorrect information, posing risks if used for decision-making or control. Generative AI outputs (e.g., novel molecules, materials) require rigorous experimental validation for plausibility, synthesizability, and real-world efficacy. AI agents controlling physical processes must be robust and safe, as failures could have serious consequences. Standardized validation methods, benchmarks, and metrics tailored for AI in diverse CBE contexts are currently lacking. Mitigation requires techniques like RAG, uncertainty quantification, human-in-the-loop review, experimental testing, and domain knowledge integration. Interdisciplinary collaboration between AI experts and domain specialists is essential for effective validation.
Integration & Implementation Hurdles	Deploying AI solutions into the operational realities of CBE faces significant practical barriers. Integrating AI seamlessly into complex environments with existing physical infrastructure, legacy IT systems, diverse sensors, and specialized equipment is technically challenging and requires standardization. Scaling AI solutions from pilot projects to full industrial operation while ensuring robustness and real-time performance presents engineering hurdles. High upfront costs for AI development, data infrastructure, hardware, and integration can be prohibitive, especially for smaller actors. A workforce skills gap exists, lacking personnel with interdisciplinary AI and CBE expertise. Organizational inertia, resistance to change, and lack of trust in AI systems can hinder adoption. The mismatch between rapid AI evolution and slower CBE infrastructure investment cycles also complicates long-term planning and integration.

18.3.1 Data Scarcity, Specificity, and Quality Requirements

Advanced AI models, particularly those based on deep learning architectures like LLMs and many GenAI systems, are notoriously data-hungry, typically requiring vast amounts of high-quality, representative data for effective training and fine-tuning (Wang, Ma, et al., 2024). However, many critical domains within CBE

present significant data challenges that act as a major bottleneck for AI application. We identify the following issues:

- Data Scarcity. Comprehensive, high-resolution, and longitudinal datasets are often lacking for key aspects of CBE. This includes detailed data on biological processes under varying conditions (e.g., microbial growth kinetics in complex waste streams), complex supply chain dynamics (e.g., real-time tracking of biomass flows, quality attributes, and associated costs across multiple actors), the long-term environmental impacts of specific CBE practices (e.g., effects of biochar application on soil health over decades), or the performance and degradation characteristics of novel bio-based materials in diverse real-world applications (Mesa et al., 2024). Generating such data, especially biological or environmental data requiring extensive fieldwork, lab analysis, or long-term monitoring, can be prohibitively expensive, time-consuming, and technically challenging.
- Data Specificity and Heterogeneity. Data relevant to CBE is often highly contextual and specific. Biomass characteristics, for instance, vary significantly depending on the source (crop type, forest residue, animal manure), geographical region, harvesting time, and storage conditions. Similarly, bioprocess performance is heavily dependent on the specific feedstocks used, the microbial strains involved, and the precise operating conditions maintained (Mesa et al., 2024). Market dynamics for niche biobased products can also be highly localized and influenced by specific regional factors. This high degree of specificity makes it difficult to train broadly generalizable AI models; a model trained on data from one region or process might not perform well in another without significant adaptation. Furthermore, CBE data exists in highly diverse formats—ranging from quantitative sensor readings and lab measurements to qualitative observations, unstructured text in reports or field notes, geospatial data from satellites or drones, economic statistics, and policy documents—posing significant challenges for data integration and processing by AI systems. General-purpose AI models, like large LLMs trained primarily on web text, often lack exposure to this specialized, domain-specific data (Walk et al., 2023; Tzachor et al., 2023).
- Data Quality. Real-world data collected from agricultural settings, forestry operations, industrial plants, or waste management facilities can suffer from numerous quality issues. These include missing values due to sensor malfunctions or incomplete reporting, measurement errors from instruments, inconsistencies between different data sources, high levels of noise, and inherent biases reflecting historical practices or sampling limitations (Mesa et al., 2024). Feeding poor-quality data into AI models can lead to inaccurate predictions, unreliable outputs, and flawed decision-making, reinforcing existing biases.

These data limitations collectively represent a major bottleneck for applying advanced AI effectively in CBE. They hinder the development of robust generative models capable of designing reliable bio-products or processes, prevent LLMs from accurately synthesizing knowledge from sparse or inconsistent sources, and limit the effectiveness of AI agents that require comprehensive and accurate data for simulation, planning, or control. This creates a pronounced “cold start” problem,

particularly for emerging CBE value chains or novel technologies where historical data is minimal. Unlike sectors with decades of digitized records, many CBE applications require substantial upfront investment in developing appropriate data collection infrastructure (sensors, monitoring protocols, data management systems) and generating sufficient high-quality data before advanced AI models can be effectively trained and deployed. This increases the initial cost, time, and complexity associated with implementing AI solutions in the CBE context.

Addressing these data challenges requires focused research efforts. Key directions include developing methods for training advanced AI models effectively with limited, sparse, or noisy data (such as few-shot learning, transfer learning techniques adapted to biological systems (Kay et al., 2024), physics-informed neural networks, and advanced data augmentation techniques including synthetic data generation (Tucker et al., 2020)). Creating common data standards, ontologies, and secure, trusted data-sharing platforms specifically designed for CBE is crucial to facilitate data integration and collaboration across stakeholders (Mesa et al., 2024). Furthermore, research is needed into robust techniques for data cleaning, imputation, anomaly detection, and quality assessment tailored to the heterogeneous biological, agricultural, and industrial datasets encountered in CBE. Finally, continued innovation in cost-effective, reliable sensing and data acquisition technologies suitable for deployment across diverse and often challenging CBE value chain environments is essential.

18.3.2 Validation, Reliability, and Effectively Managing "Hallucination" Risk

Ensuring the trustworthiness, reliability, and accuracy of outputs generated by advanced AI systems is paramount for CBE, especially when these systems are applied in scientific research, industrial process control, environmental monitoring, or policy decision-making with significant environmental and economic consequences. Several specific reliability concerns arise prominently with the newer generation of AI tools like GenAI, LLMs, and AI agents.

A widely discussed issue is LLM Hallucination. LLMs have a known propensity to generate hallucinations—responses that sound plausible, confident, and grammatically correct but are factually incorrect, nonsensical, or not supported by the input data or established knowledge (Digital Ocean Community, 2024). Relying on such hallucinated information for critical tasks in CBE, such as designing experiments, interpreting scientific results, making policy decisions based on AI-generated summaries, or controlling sensitive bioprocesses, could lead to significant errors, safety risks, wasted resources, or environmental damage (De Clercq et al., 2024).

Similarly, ensuring the Generative AI Reliability is critical when these tools are used for design and discovery. When GenAI is used to propose novel molecules, materials, enzymes, or biological systems, the reliability of these computationally

generated outputs must be rigorously confirmed. Generated designs need thorough validation for physical plausibility (e.g., is the proposed molecule stable?), chemical synthesizability, or biological viability, and critically, whether they exhibit the predicted beneficial properties (e.g., enhanced biodegradability, desired catalytic activity, improved material strength) under real-world conditions (Wen et al., 2025).

Over-reliance on unvalidated AI designs could lead to costly failures in downstream development (Robert et al., 2020).

For AI Agent Robustness and Safety, particularly when agents are designed for simulation, control, or autonomous operation in physical environments, ensuring they behave reliably and safely under all conditions is vital. Agents must be robust to unexpected inputs (e.g., sensor noise or failure), malfunctions in the tools they use, ambiguous instructions, or unforeseen changes in their operating environment (Digital Ocean Community, 2024). Failure modes in autonomous agents controlling physical processes, such as regulating a bioreactor, managing irrigation systems, or operating waste handling machinery, could potentially have serious safety implications for workers or lead to significant environmental incidents (Cheng et al., 2023).

Compounding these issues is the general Lack of Standardized Validation Methods for advanced AI in specific domains like CBE. Rigorously validating the performance of AI, especially for complex generative or agentic tasks, remains a significant research challenge. There is often a lack of widely accepted benchmarks, standardized evaluation metrics, and agreed-upon methodologies specifically tailored for evaluating AI applications within the diverse contexts of the bioeconomy (Robert et al., 2020). Furthermore, commonly used validation metrics themselves can have limitations or may not capture all aspects of real-world performance, requiring critical assessment of the validation process itself.

Mitigating these reliability risks requires a multi-pronged approach. Strategies include employing techniques like RAG to ground LLM responses in verified external knowledge sources, incorporating uncertainty quantification methods so that models can indicate their level of confidence in an output, prompting models to generate multiple diverse outputs for comparison or user selection (Digital Ocean Community, 2024), implementing rigorous human-in-the-loop review and validation processes where experts scrutinize AI outputs before they are acted upon (Tzachor et al., 2023), and conducting thorough experimental testing and field trials of AI-generated designs or process recommendations. Integrating domain-specific scientific knowledge or physical constraints directly into AI models (e.g., enforcing conservation laws in simulations) can also improve their reliability and plausibility (Sarailidis et al., 2023). Developing domain-specific benchmarks and standardized evaluation protocols is crucial for enabling comparative assessment and tracking progress (Robert et al., 2020). Table 18.4 outlines some key reliability challenges and potential mitigation strategies.

Figures 18.3 and 18.4 illustrate a practical implementation of hallucination mitigation strategies in climate data analysis developed by Cao et al. (2024). Their approach demonstrates how AI reliability issues can be addressed through a three-stage framework that connects LLMs with verified data sources and sandboxed code execution. Rather than relying on the LLM's pre-trained knowledge (which

Table 18.4 Strategies for mitigating AI reliability issues in CBE applications

Reliability Challenge	Mitigation Strategy Example	Primary Application Context	Key Consideration & Limitations
LLM Hallucination	Retrieval-Augmented Generation (RAG) Cross-checking against External databases/literature	Knowledge synthesis, Decision support, Technical Q&A	Requires high-quality, up-to-date, curated knowledge base; Retrieval accuracy is crucial; Requires reliable external sources/APIs; May be slow/costly; Coverage may be incomplete.
LLM Uncertainty	Output Uncertainty Quantification/Confidence Scoring	Decision Support, prediction, Q&A	Methodological complexity; Interpretation of scores can be difficult; Calibration needed.
GenAI Output Plausibility	Integration with Physics/Chemistry Simulators	Material, Molecule, and Protein Designs	High computational cost; accuracy limited by simulator fidelity; integration complexity.
GenAI Output Validation	Experimental Validation (Lab Synthesis & Testing)	Material/Molecule Design, Enzyme Eng., Process Design	Gold standard for proof, but time-consuming, expensive, requires specialized lab facilities/expertise.
GenAI & Agent Reliability	Rigorous Human Expert Review and Oversight	All Generative Tasks, Critical Decisions, Control	Can catch subtle errors, adds domain context, but subject to expert bias/availability, scalability issues.
Agent Robustness	Red Teaming/Adversarial Testing/Simulation of Edge Cases	Autonomous Control, Simulation, Planning	Helps identify failure modes, but difficult to define all realistic failures; test coverage limitations.
Agent Safety	Safety guardrails/defined operating; constraints/rule-based overrides	Autonomous Control (Physical Systems)	Effective for known risks, but defining appropriate constraints is complex and may limit adaptability.
Agent Safety Assurance	Formal verification methods	Safety-critical control systems	Provides high assurance for properties verified, but suffers from scalability challenges for complex agents/environments.

(continued)

Table 18.4 (continued)

Reliability Challenge	Mitigation Strategy Example	Primary Application Context	Key Consideration & Limitations
General Validation Need	Development of domain-specific benchmarks & metrics	All AI Applications in CBE and broader use	Essential for progress tracking, but requires community consensus, data availability, maintenance; Increases confidence in generalizability, but requires data sharing agreements, standardization efforts.

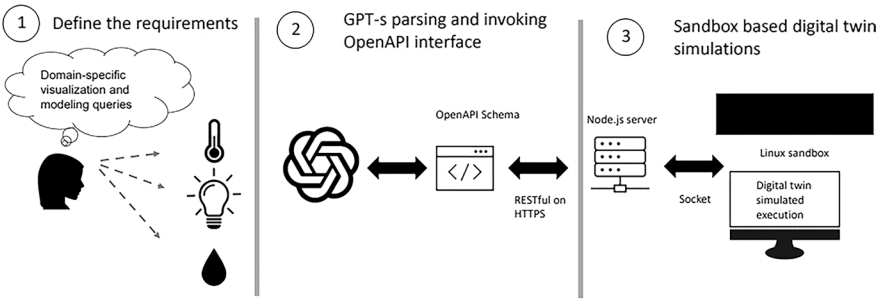

Fig. 18.3 Architecture for mitigating LLM hallucinations in climate data analysis: A three-stage framework connecting user queries to verified data sources and sandboxed execution

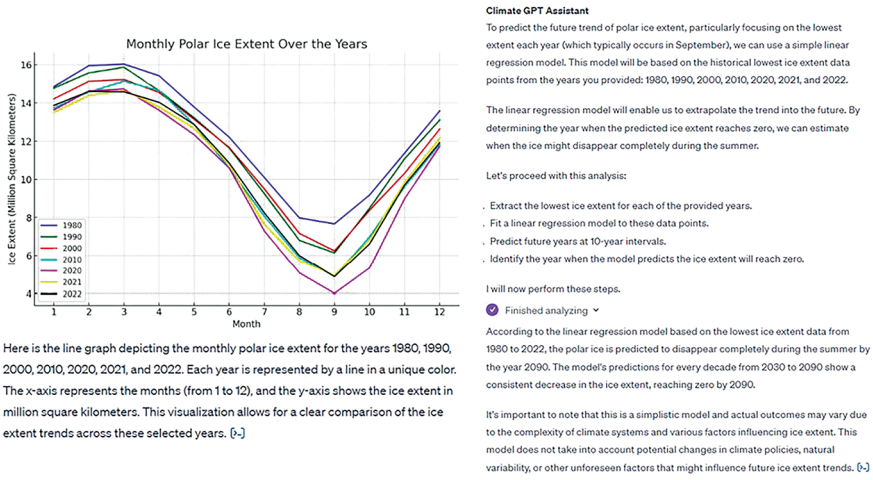

Fig. 18.4 Example of data-grounded LLM analysis: Climate GPT assistant demonstrating RAG implementation with direct data retrieval and python code execution for polar ice extent modeling

may contain inaccuracies), the system retrieves actual climate data through APIs and executes Python code in a controlled environment, ensuring results are always based on real, current data. This exemplifies how RAG systems can be effectively deployed in the context of CBE, particularly for analysis of complex environmental and agricultural datasets. Such architectures are essential for ensuring AI-generated insights remain firmly grounded in scientific reality rather than computational artifacts.

A critical aspect of validation in CBE context is its inherently interdisciplinary nature. AI algorithms operate based on patterns learned from data, but their output must ultimately be valid and meaningful within the complex realities of biological, chemical, ecological, and economic systems. Assessing this real-world validity—determining if a computationally generated molecule is stable and effective in a biological system, if a predicted crop yield is realistically achievable under field conditions, or if a simulated environmental impact accurately reflects ecological processes—requires deep domain expertise that goes far beyond AI development itself (Robert et al., 2020). Therefore, effective validation frameworks for AI in CBE must involve close, iterative collaboration between AI specialists and domain experts (such as biologists, chemists, engineers, agronomists, ecologists, economists), integrating computational verification techniques with domain-specific experimental validation and critical expert review (McKay et al., 2022).

Key research needs in this area include the development of robust, scalable, and cost-effective validation methodologies specifically designed for GenAI, LLMs, and AI agents applied to diverse CBE problems (e.g., validating generated biomolecules, assessing agent safety protocols in process control). Further research is needed on techniques to reliably detect, quantify, and mitigate hallucinations in LLMs, particularly when they process complex scientific, biological, or chemical information (Hagendorff et al., 2022; Lin et al., 2024). Methods for formal verification and safety assurance of autonomous AI agents operating in safety-critical CBE applications (e.g., bioreactor control, autonomous farm machinery, waste handling robotics) need significant advancement (IBM Research, 2024; Mitra & Murthy, 2022). Finally, the creation of standardized, high-quality benchmark datasets and universally accepted evaluation metrics is essential for rigorously comparing the performance and reliability of different AI approaches on specific CBE tasks, with particular attention to explainable AI metrics (Robert et al., 2020).

18.3.3 Integration and Implementation Hurdles in CBE Systems

Successfully deploying advanced AI solutions beyond the laboratory or pilot stage and integrating them effectively within the operational realities of CBE faces numerous practical integration and implementation challenges. Moving from promising algorithms demonstrated in controlled environments to functional,

value-generating systems used routinely by farmers, factory operators, or policy-makers requires overcoming significant technical, economic, and organizational hurdles.

A major challenge lies in System Integration Complexity. CBE operations often involve a heterogeneous mix of existing physical infrastructure (such as farms with varying levels of technology, established forestry operations, diverse processing plants, existing waste collection and treatment facilities), legacy IT systems that may not be designed for interoperability, diverse sensor networks using different protocols, and specialized operational equipment. Integrating advanced AI tools seamlessly into this complex, often pre-existing, environments is a significant technical undertaking (Schipfer et al., 2024; Perla, 2025). Ensuring interoperability between new AI platforms, various data sources (databases, sensor streams, manual inputs), existing control systems (e.g., SCADA systems in factories), and enterprise resource planning (ERP) software requires considerable technical effort, adherence to standards (where they exist), and potentially the development of custom middleware (Kemnitz et al., 2023; Adeyeye & Akanbi, 2024).

Relatedly, issues of Scalability and Robustness are critical for AI solutions in CBE. AI solutions developed and tested in controlled research settings or small-scale pilot projects may not readily scale to meet the demands and rigors of full industrial or agricultural operation. Handling significantly larger data volumes efficiently, ensuring real-time performance for time-sensitive control applications, maintaining model robustness and accuracy in the face of variable real-world conditions (e.g., changing weather, fluctuating feedstock quality), and managing fleets of AI-driven devices (like agricultural robots, sorting machines, or monitoring sensors) present substantial engineering challenges (Heinrich et al., 2019; Martínez-Arellano & Ratchev, 2024). Reliability in continuous, demanding operational environments is often much harder to achieve than in short-term demonstrations (Gao et al., 2023; Behdin et al., 2025).

The High Initial Costs associated with implementing advanced AI solutions often represent a significant barrier to adoption, particularly for smaller enterprises or actors in primary production sectors like agriculture and forestry (Sapkota et al., 2022; Hampel & Fabulya, 2024). These costs include expenses related to AI model development, licensing, or acquisition; necessary upgrades to data infrastructure (deploying new sensors, improving data storage and networking capabilities); acquisition of specialized computing hardware (e.g., GPUs for model training or inference); fees for system integration services; and potentially the costs of retrofitting existing physical equipment to make it compatible with AI control systems (Yeboah, 2025; Akintuyi, 2024). These substantial upfront investments can be difficult to justify, especially if the return on investment (ROI) is uncertain or long-term (Alkhafaji et al., 2024).

A widespread challenge is the Workforce Skills Gap. There is often a shortage of personnel within CBE organizations who possess the necessary interdisciplinary skills required to effectively develop, deploy, manage, maintain, validate, and interpret the outputs of advanced AI systems in their specific context (Harmani et al., 2022; Malathi & Senbagam, 2024). This includes a need for data scientists, AI

engineers, and software developers who are also familiar with the nuances of biological systems or CBE processes, as well as domain experts (agronomists, chemical engineers, ecologists) who are trained to work effectively alongside AI tools and critically evaluate their recommendations (Gul & Banday, 2024; Fuentes & Tongson, 2021). Bridging this skills gap requires significant investment in targeted training programs, vocational education, and university curricula reform (Shurpali et al., 2025; Akanbi et al., 2025).

Finally, Organizational Inertia and User Acceptance can pose significant non-technical barriers. Implementing AI often necessitates changes to long established workflows, existing job roles, and traditional decision-making processes. Overcoming organizational resistance to change, building trust in AI-generated recommendations or automated actions among operators, managers, and other end-users, and ensuring that AI interfaces are user-friendly and intuitive are crucial for successful adoption and integration (Majeed et al., 2024; Dmitrović et al., 2024). Demonstrating clear value propositions early on and involving end-users throughout the design and implementation process can help mitigate these challenges and foster buy-in (Reddy et al., 2024; Thakkar & Kumar, 2024).

Further complication arises from the potential mismatch between the extremely rapid pace of AI development and the typically slower investment cycles and physical inertia characteristic of much CBE infrastructure. AI models and capabilities evolve remarkably quickly (Srivastava et al., 2025; Xu, 2024), while investments in major capital assets like biorefineries, agricultural machinery, waste processing facilities, or forestry equipment often have very long operational lifecycles (Mouzakitis & Adamides, 2022; Sönmez & Çetin, 2024). Integrating a state-of-the-art AI system might require significant time and capital expenditure for infrastructure adaptation, by which point the AI technology itself may have advanced further, potentially rendering the initial investment outdated. This dynamic makes long-term strategic planning difficult and highlights the need for flexible, modular, and adaptable AI integration strategies that can accommodate future upgrades or component replacements without requiring complete system overhauls (Kemnitz et al., 2023; Lai & Chew, 2022).

Overcoming these integration and implementation hurdles requires focused research and development efforts. Key areas include the development of standardized APIs, middleware solutions, and interoperability protocols specifically designed to simplify the integration of AI tools into diverse CBE hardware and software ecosystems. Research into cost-effective and scalable deployment architectures for AI in CBE, potentially leveraging cloud platforms, edge computing, fog computing, or hybrid approaches tailored to specific needs (e.g., connectivity constraints in rural areas), is also needed. Frameworks and best practices for managing the entire lifecycle of AI models in CBE applications—including continuous monitoring of performance, periodic retraining, version control, secure updating, and simulation optimization—must be established. Developing effective training programs and educational curricula to build the necessary AI skills within the existing and future CBE workforce is paramount (Isoko et al., 2024). Studies on organizational change management strategies specifically tailored to facilitate AI adoption in

traditional CBE sectors like agriculture, forestry, and bio-based manufacturing are also valuable (Shafik, 2024). Finally, research into modular AI architectures (e.g., extending concepts like Modular RAG (Digital Ocean Community, 2024) that allow for easier upgrading or swapping of individual components could help address the challenge posed by differing technology evolution speeds.

18.4 Future Outlook and Research Agenda

The integration of advanced AI into the fabric of CBE is still in its early stages, but the trajectory points toward increasingly sophisticated, pervasive, and potentially impactful applications in the coming years. Understanding the emerging trends, anticipating potential breakthroughs, and identifying the critical research questions that need to be addressed is essential for guiding future development efforts and maximizing the positive contribution of AI toward achieving a truly sustainable and CBE.

18.4.1 Emerging Trends and Potential Breakthroughs in AI for CBE

Several key technological trends and potential breakthroughs are likely to shape the future landscape of AI within CBE. One significant trend is toward Increasing Agent Autonomy. The capabilities of AI agents are rapidly improving, moving beyond simple automation toward systems that can manage complex CBE operations with greater independence and adaptability (IBM Research, 2024). In the future, we can expect to see more sophisticated autonomous systems designed for tasks such as optimizing biorefinery processes in real-time based on fluctuating inputs and market signals, managing farm operations adaptively based on dynamic environmental conditions and sensor feedback, coordinating complex waste collection and logistics networks dynamically, or even conducting autonomous environmental monitoring and rapid response actions.

Another major frontier is AI-Driven Scientific Discovery at Scale. The use of Generative AI and sophisticated AI agents is poised to revolutionize the discovery and design of novel bio-based solutions relevant to CBE (Future Today Institute, 2024). The emerging concept of an AI Scientist—AI systems potentially capable of formulating hypotheses, designing experiments, interpreting complex data, and drawing plausible conclusions with minimal human guidance—could dramatically accelerate the pace of innovation in critical areas like sustainable material science, enzyme engineering for biocatalysis, synthetic biology for producing bio-products, and the development of novel sustainable chemical processes (Hagendorff et al., 2022). This potential extends beyond merely mimicking nature; advanced AI might enable the rational design of bio-inspired or entirely novel biological systems and

materials that exceed the efficiency, resilience, or functionality of their natural counterparts, leading to potential breakthroughs in areas like resource conversion efficiency, carbon capture, or material performance (IBM, 2024).

The trend toward Hyper-Personalization, driven by AI's ability to analyze individual-level data and preferences, could also extend into CBE. This might manifest as customized bio-based nutritional products tailored to individual dietary needs or health goals, materials designed with specific properties for personalized applications (e.g., in medicine or consumer goods), or highly tailored agricultural management plans optimized for specific micro-climates, soil conditions, and farmer objectives (Wally Boston, 2024).

The impact of AI will be significantly amplified through its Synergistic Integration with Other Advanced Technologies. Combining AI's analytical and decision-making power with the ubiquitous sensing capabilities of the Internet of Things (IoT), the potential for transparent and secure traceability offered by blockchain in supply chains (Saidu et al., 2025), the dexterity and precision of advanced robotics for automation, and the comprehensive system simulation capabilities of digital twins (MacArthur, 2019) will enable the creation of far more sophisticated, interconnected, efficient, and resilient CBE solutions than any single technology could achieve alone (Zhang et al., 2023; Chawla et al., 2023).

A specific area of rapid advancement is likely to be Generative Biology. The focus is shifting from GenAI primarily creating digital content (text, images) toward "generative biology," where AI models directly design novel biological entities—such as molecules with specific binding properties, proteins with tailored catalytic functions, synthetic metabolic pathways, engineered cells, or even simple functional organisms—with specific functions optimized for CBE applications. Examples include designing microbes for highly efficient waste degradation, creating biological systems for effective carbon capture and utilization, or engineering organisms to produce novel bio-based materials (Future Today Institute, 2024).

AI tools are also expected to become integral to Enhanced Circularity Assessment and Management. Future AI systems will likely automate and improve the accuracy and efficiency of methodologies like Life Cycle Assessments (LCA) and Material Flow Analyses (MFA). They could enable real-time tracking and reporting of circularity indicators across complex, multi-stage value chains, providing better feedback loops for continuous improvement and optimization efforts toward greater circularity UIDP (University-Industry Demonstration Partnership, 2024).

Finally, the deployment of Edge AI for Distributed Intelligence will become increasingly important. Processing AI algorithms directly on local devices—such as sensors deployed in fields, agricultural machinery, handheld diagnostic tools, or small-scale processing units—known as Edge AI, will enable real-time decision-making and control in distributed CBE settings without relying on constant, high-bandwidth cloud connectivity. This is crucial for applications like precision agriculture in remote areas, real-time environmental monitoring networks, decentralized waste processing facilities, and ensuring operational continuity even with intermittent network access (Chawla et al., 2023).

18.4.2 Critical Research Questions and Future Directions

To navigate the path toward an AI-enhanced CBE effectively, responsibly, and equitably, significant and focused research efforts are required across multiple disciplines. Building upon the specific gaps identified throughout the challenges discussed in Sect. 3, critical future research directions should include a continued and intensified focus on Addressing Foundational Challenges. Overcoming the core difficulties related to data (scarcity, quality, heterogeneity, access, bias), validation (ensuring reliability, mitigating hallucination, developing benchmarks), integration (scalability, interoperability, cost-effectiveness, usability), ethics (bias detection and mitigation, environmental footprint assessment, ensuring fairness and accountability, managing labor impacts), and policy (developing adaptive governance, ensuring coherence, setting standards) remains paramount for widespread and beneficial AI adoption in CBE (Mesa et al., 2024).

Beyond these foundational aspects, research is needed to Develop Domain Specific AI Models for CBE. Creating advanced AI models (GenAI, LLMs, Agents) that are specifically pre-trained or fine-tuned on large, high-quality datasets highly relevant to specific CBE domains (e.g., agricultural genomics, proteomics, soil science data, chemical process data, forestry inventories, waste stream characterization data) is necessary to significantly improve their performance, reliability, and contextual understanding on specialized tasks compared to general-purpose models.

Advancing Hybrid AI-Physics Modeling approaches holds significant promise. Integrating first-principles knowledge derived from physics, chemistry, and biology directly into the architecture or training process of data-driven AI models can create more robust, interpretable, and generalizable models, especially for simulating and controlling complex bioprocesses or ecological systems where data may be sparse but underlying scientific principles are well understood (Subha et al., 2024).

Progress in Causality and Explainable AI (XAI) tailored for CBE is critical. Research should focus on advancing causal inference methods to move beyond identifying correlations in complex CBE data toward understanding underlying cause-and-effect relationships, which is essential for effective intervention design. Developing XAI techniques that are suitable for explaining the reasoning processes of advanced AI models (especially opaque systems like LLMs and complex agents) in biological, environmental, and socio-economic contexts is crucial for building user trust, facilitating debugging, ensuring accountability, and enabling meaningful human oversight.

Designing and evaluating effective Human-AI Collaboration Frameworks is another key research area. This involves creating intuitive user interfaces, developing shared decision-making protocols that leverage the complementary strengths of humans and AI, establishing mechanisms for humans to effectively supervise, interact with, and provide feedback to increasingly autonomous AI agents, and understanding how to best integrate AI insights into existing human workflows and expertise.

There is a pressing need for Holistic Sustainability Assessment of AI in CBE. Research should focus on developing comprehensive and standardized

methodologies to assess the net sustainability impact—considering environmental (e.g., energy use, emissions, resource use, biodiversity effects), social (e.g., equity, labor, community impacts), and economic dimensions—of deploying specific AI solutions within CBE value chains over their entire lifecycle. Crucially, this assessment must include the environmental and resource footprint of the AI system itself to ensure a true net benefit.

Further research is required on applying AI for Systems-Level Optimization of the entire CBE. This involves investigating the application of advanced AI techniques, particularly multi-agent systems, reinforcement learning, and complex optimization algorithms, to model, simulate, and optimize interconnected CBE systems at regional, national, or even global scales. Such research must explicitly account for complex interactions between sectors, feedback loops, inherent uncertainties, potential trade-offs between multiple competing objectives (e.g., maximizing economic output versus preserving biodiversity), and the diverse interests and behaviors of multiple stakeholders FEWSUS Project (University of Tennessee, 2024).

Finally, creating Adaptive and Resilient AI Systems is essential for the dynamic context of CBE. Research should focus on developing AI systems for CBE applications that are not only efficient under stable conditions but are also inherently adaptive to changing circumstances (such as climate variability, market shifts, new regulations, or evolving consumer preferences) and resilient to potential disruptions (like supply chain shocks, sensor failures, or cyberattacks) (Chawla et al., 2023; Grace & Joice, 2025).

Given the inherently interdisciplinary nature of both advanced AI and CBE, achieving significant progress hinges on fostering deep, sustained, and effective collaboration between AI researchers and domain experts from a wide range of fields, including biosystems engineering, soil science, agriculture, forestry, chemical engineering, ecology, economics, social sciences, and policy science. The current fragmented nature of research at this intersection, as noted by some studies, suggests a strong need for a more coordinated and strategic approach. Developing a shared CBE-AI Research Roadmap, potentially through inclusive multi-stakeholder processes involving academia, industry, government agencies, and civil society UIDP (University-Industry Demonstration Partnership, 2024), could help prioritize key research areas, align efforts across institutions and countries, foster necessary collaborations, and strategically channel resources toward developing the most impactful and responsible AI solutions for advancing CBE globally (Stockholm Environment Institute [SEI], 2024; Ahenkora, 2025).

18.4.3 Concluding Perspective: Navigating the Path Toward AI-Enhanced CBE

Advanced AI—encompassing the powerful capabilities of Generative AI, LLMs, and increasingly sophisticated AI Agents—holds transformative potential for accelerating the complex and urgently needed transition toward a truly sustainable and

CBE. These cutting-edge technologies offer a powerful new toolkit to drive innovation in the design of bio-based products and processes, enhance the efficiency, control, and resilience of complex bioprocesses and supply chains, enable sophisticated system simulation and prediction for better planning and risk management, synthesize vast amounts of disparate knowledge to support more informed decision-making, and facilitate effective communication and collaboration among the diverse stakeholders essential for CBE success.

However, realizing this considerable potential requires careful and deliberate navigation of significant challenges and potential pitfalls. Hurdles related to data scarcity, specificity, and quality remain fundamental constraints. The critical need for robust validation processes and assurances of AI reliability, including mitigating risks specific to new models like LLM hallucinations, cannot be overstated. Practical difficulties in integrating AI solutions seamlessly and cost-effectively into existing CBE systems and workflows pose significant barriers to adoption. Profound ethical considerations—spanning the environmental impact of AI itself to crucial issues of social equity, data privacy, labor impacts, and accountability—must be proactively identified and addressed. Furthermore, the need for adaptive, coherent, and enabling policy and governance frameworks that can keep pace with technological change while upholding societal values is paramount.

The path forward demands a balanced, nuanced, and critical perspective. It is crucial to harness the immense power of AI as an enabler for achieving core CBE goals—resource efficiency, waste minimization, regeneration of natural systems, and sustainable production—while diligently and continuously working to mitigate its potential negative consequences. We must ensure that the deployment of AI aligns strictly with fundamental principles of sustainability, circularity, environmental stewardship, and social justice. AI should be viewed and utilized as a powerful tool within the broader strategic framework of CBE, not as a purely technological panacea that can solve deeply complex systemic problems in isolation (Fer et al., 2021). Human judgment, ethical considerations, and domain expertise must remain central.

Ultimately, successfully leveraging advanced AI to help build a truly sustainable and CBE demands a concerted, collaborative, and ongoing effort from all involved parties. This includes sustained public and private investment in targeted, interdisciplinary research and development. It requires fostering close and genuine collaboration between AI experts and CBE domain specialists from diverse fields. It demands the establishment of thoughtful, adaptive, and participatory governance structures. It necessitates significant efforts in education and workforce development to build the required skills across sectors. Most importantly, it requires an unwavering commitment to ensuring that ethical considerations and fundamental sustainability principles guide every step of AI design, development, deployment, and operation within the CBE landscape. Only through such a deliberate, responsible, and holistic approach can the full potential of advanced AI be unlocked to contribute meaningfully and positively to a more sustainable, equitable, and prosperous future for all.

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Chapter 19
One Health-Centric Circular Bioeconomy

Ashley Noel Morgan and Debra Lee Miller

19.1 Defining One Health

One Health is an approach used to tackle complex and "wicked" problems without straightforward solutions. Although not a rigorous theoretical model, the goal of this approach is to build teams composed of diverse sectors, disciplines, and stakeholders to develop ways to best mitigate these challenges. One Health recognizes that the health of humans, animals, plants, and the environment is inextricably connected and that you cannot impact the health of one of those groups without impacting the others. In 2021, a One Health High Level Expert Panel (OHHLEP), appointed as the One Health advisory group for Quadripartite organizations: the Food and Agriculture Organization of the United Nations (FAO), United Nations Environment Programme (UNEP), World Health Organization (WHO), and World Organisation for Animal Health (WOAH), put forth the following as the official definition of One Health, which was accepted by the Quadripartite organizations (Panel (OHHLEP) et al., 2022).

(Inset): One Health is an integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals, and ecosystems. It recognizes that the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems) is closely linked and interdependent. The approach mobilizes multiple sectors, disciplines, and communities at varying levels of society to work together to foster well-being and tackle threats to health and ecosystems, while addressing the collective need for clean water, energy, and air, safe and nutritious food, taking action on climate change, and contributing to sustainable development (Panel (OHHLEP) et al., 2022).

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Applying a One Health approach is vital to identify solutions toward the health and survival of our planet. The Anthropocene, which describes our current geologic time period during which human activity has had a significant impact on the planet's climate and ecosystem, marks a time of accelerated change. Climate alterations and species extinctions are not novel occurrences, but the rate at which they are occurring precludes adequate, planet-wide adaptation. This results in loss of biodiversity and resultant ecosystem instability, implying a need to further study and understand the consequences of anthropogenic stressors to lessen (or eliminate) damage. This evolutionary view of development is central to the adaptability of both the One Health approach and the future of the Circular Bioeconomy (Zilberman et al., 2018).

19.2 One Health and the Circular Bioeconomy

The One Health approach applies to the Circular Bioeconomy through several overlapping goals: resource efficiency, biodiversity, sustainable agriculture, and interdisciplinary research (Fig. 19.1). Resource efficiency involves reducing

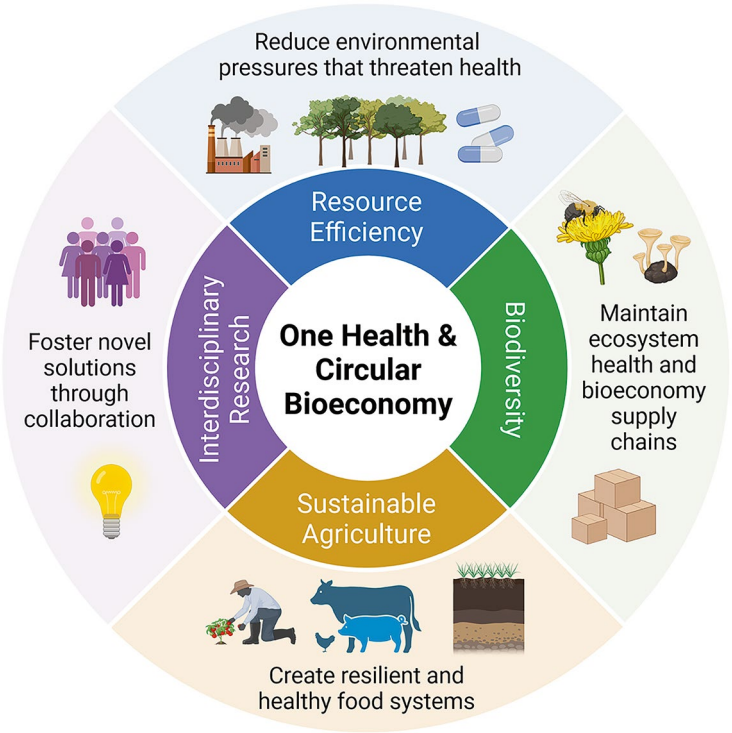

Fig. 19.1 One Health and the circular bioeconomy. Common goals between two conceptual approaches

environmental pressures that threaten health. One Health promotes practices that reduce environmental contamination, such as responsible pharmaceutical use and waste disposal to prevent antimicrobial resistance (AMR), and the Circular Bioeconomy focuses on minimizing waste through recycling and reusing biological resources, such as converting agricultural and animal waste into bioenergy or biofertilizers. Both approaches aim to minimize waste while maximizing the value of renewable resources, reducing environmental pressures that threaten human, animal, and ecosystem health. Also, life relies on diversity to function efficiently and effectively, thus protecting biodiversity is crucial to maintaining ecosystem health and balance. One Health highlights the role of healthy ecosystems in preventing disease outbreaks and preserving important ecosystem services, while the Circular Bioeconomy relies on the regeneration of ecosystems to provide renewable biological resources sustainably. The prioritization of biodiversity and maintaining ecosystem balance benefits both bioeconomy supply chains and the prevention of global health crises. Sustainable agriculture involves creating resilient and healthy food systems. From a One Health perspective, this includes supporting integrated practices like agroecology to ensure food safety, animal welfare, and environmental health, while the Circular Bioeconomy promotes the development of sustainable, closed-loop agricultural systems where by-products are reused, reducing waste and reliance on non-renewable inputs. Both seek to create resilient food systems that are health-conscious and environmentally sustainable. The creation of this type of food system includes a focus on climate resiliency and the recognition of the impact of climate change on disease patterns and ecosystem health as well as the necessity to identify adaptive health interventions and innovative technologies to reduce greenhouse gas emissions. Furthermore, the One Health approach and the Circular Bioeconomy both rely on interdisciplinary research and cross-sector collaborations to foster novel solutions addressing complex, global challenges. These collaborations can drive innovation and engage stakeholders so that these solutions can be efficiently and sustainably implemented.

To maximize the health (quality and often also quantity) of bioproducts and the planet more broadly, a One Health approach must be applied. To do so effectively will surely necessitate members of the general public (consumers) as well as producers, distributors, supply-chain experts, policy makers, educators, medical professionals, researchers, and many others all exploring ways to improve resources generated while protecting the ecosystems from which they are derived. In the following section, we will discuss how this type of exploration can be accomplished through building a One Health-centric Circular Bioeconomy with a focus on healthy environments, microbes, plants, animals, and humans.

19.3 Building a One Health-Centric Circular Bioeconomy

19.3.1 Healthy Environment

A healthy environment begins with a healthy "base," and a circular bioeconomy can only thrive within an environment that encompasses healthy soil, clean water, and clean air. These elements are interconnected and foundational to all forms of life, serving as the bedrocks of sustainable ecosystems. Rich in organic matter and diverse microbial life, healthy soil enhances nutrient cycling, improves water retention, and promotes plant growth (Ortíz-Castro et al., 2009; Prasad et al., 2021; Coban et al., 2022). This biodiversity within the soil contributes to the resilience of crops, protecting plants against biotic and abiotic stressors and making them more resistant to pests and diseases while reducing the need for synthetic fertilizers and pesticides (Vannier et al., 2019). By fostering healthy soil, farmers can enhance productivity while minimizing their ecological footprint, thus aligning with the principles of a circular bioeconomy. Furthermore, healthy soil is integral to carbon sequestration, a critical process in mitigating climate change (Dynarski et al., 2020). By capturing and storing carbon from the atmosphere, well-managed, and ideally untilled, soils can help reduce greenhouse gas emissions and contribute to overall environmental health (Dynarski et al., 2020) (Chap. 11—Zilberman). Additionally, healthy soils support the growth of diverse plant species, which, in turn, provide habitats for various organisms and promote biodiversity. This interconnectedness, highlighted using a One Health approach, ensures that all components of the ecosystem—plants, animals, and microorganisms—thrive in a balanced manner.

Clean water is equally essential to a circular bioeconomy, serving as a vital resource that supports human health, agricultural productivity, and ecosystem integrity. Access to clean water is crucial for irrigation, enabling sustainable farming practices that enhance crop yields while minimizing the use of harmful chemicals. Healthy water systems, including rivers, lakes, and even small waterbodies, can support biodiversity by providing habitats for various aquatic and terrestrial species (Biggs et al., 2017). In a circular bioeconomy, efficient water management practices—such as rainwater harvesting, water recycling, and sustainable watershed management—ensure that water is used wisely and responsibly, reducing waste and protecting this precious resource (Martinez de Arano et al., 2018). Additionally, clean water plays a significant role in safeguarding public health and preventing the spread of waterborne diseases. Ensuring that communities have access to safe drinking water promotes the well-being of both humans and animals, reducing healthcare costs and enhancing productivity (Hutton et al., 2007). Moreover, healthy aquatic ecosystems contribute to nutrient cycling and filtration, improving water quality and supporting the overall resilience of the environment (Maltby & Acreman, 2011). In this context, protecting and restoring water bodies not only supports biodiversity but also enhances the sustainability of agricultural practices and local economies (Maltby & Acreman, 2011). Ultimately, clean water is a cornerstone of a circular

bioeconomy, reinforcing the interconnectedness of human, animal, plant, and environmental health (i.e. "One Health").

Clean air and reduced emissions are critical components of a circular bioeconomy, as they directly contribute to environmental health and public well-being. Maintaining air quality is essential for the overall health of ecosystems, human populations, and animals. Pollutants such as particulate matter, nitrogen oxides, and volatile organic compounds can harm respiratory health and disrupt natural processes. By implementing practices that reduce emissions—such as utilizing renewable energy sources, promoting energy efficiency, and adopting sustainable transportation methods—communities can significantly improve air quality (Litman & Burwell, 2006; Omer, 2008). This not only benefits public health by reducing respiratory diseases but also enhances the resilience of ecosystems that are sensitive to air pollution. In a circular bioeconomy, clean air supports biodiversity and the functioning of natural systems (Lovett et al., 2009). Healthy air quality fosters robust plant growth, which in turn contributes to carbon sequestration and climate regulation (Lovett et al., 2009). Although some plants are more efficient than others at this task, plants act as natural air filters, absorbing carbon dioxide and releasing oxygen, thereby playing a vital role in mitigating climate change (Vieira et al., 2018). Moreover, reduced emissions from agricultural practices, such as organic farming and integrated pest management, contribute to healthier ecosystems by minimizing the release of harmful, aerosolized chemicals into the atmosphere (Lorenz & Lal, 2016). By prioritizing clean air and emission reduction, a circular bioeconomy can foster a sustainable environment that benefits all living organisms, promoting a cycle of health and resilience that supports long-term ecological balance.

By focusing on regenerative practices that restore soil health, enhance water quality, and reduce air pollution, communities can foster an environment conducive to a productive and sustainable circular bioeconomy. Such an environment not only supports human well-being but also promotes ecosystem resilience, which is vital in facing the challenges posed by climate change and industrialization.

19.3.2 Healthy Microorganisms

In a One Health approach to the Circular Bioeconomy, the role of healthy microbes cannot be overstated. Microbial communities are the unsung heroes of ecological balance, influencing nutrient cycling, plant and animal health, and contributing to environmental remediation (Chap. 15—Seeger). A robust microbiome supports biodiversity, acting as a buffer against pathogens and environmental stressors (Vannier et al., 2019). Also, microbes are capable of metabolizing harmful environmental contaminants such as pesticides, polychlorinated biphenyl (PCBs), heavy metals, petroleum-derived hydrocarbons, plastics, and others (Chap. 15—Seeger). These essential bioremediation services should not be discounted when accounting for the role of microbes in the Circular Bioeconomy. This interconnectedness means that

disruptions in microbial health can have cascading effects throughout the ecosystem, impacting plants, animals, and humans alike. By incorporating strategies that enhance microbial diversity—such as composting, cover cropping, and the reduced use of synthetic fertilizers—communities can harness the power of these microorganisms (Lorenz & Lal, 2016).

Antimicrobial resistance (AMR) poses a significant threat to the health of microbes in the environment, impacting ecosystems and the health of all resident organisms. When antimicrobial agents are overused or misused—whether in healthcare, agriculture, or aquaculture—resistant strains can emerge, disrupting the balance of microbial communities. This disruption can lead to a decline in beneficial microbes that are essential for processes like nitrogen fixation and organic matter decomposition, ultimately harming ecosystem functionality, circularity, and resilience (Wang et al., 2021). One aspect of the common resource efficiency goal of One Health and the Circular Bioeconomy (Fig. 19.1) is proper waste management. This includes the responsible handling of pharmaceuticals to prevent their unintended disposal or discharge into the environment. This type of environmental contamination can lead to higher concentrations of antimicrobial resistant microbes and thus an amplification of horizontal transfer of AMR genes (Kotwani et al., 2021). Moreover, the presence of resistant microbes in the environment can complicate efforts to control pathogens, as traditional antimicrobial treatments may become ineffective. This can result in increased morbidity and mortality from infections and place additional strain on healthcare systems (Ferri et al., 2017). In agricultural contexts, it should be noted that effective antimicrobials are important for maintaining the health and welfare of livestock and thus the economic stability of farms (Founou et al., 2021); however, their misuse can negatively affect livestock health and food safety, leading to economic losses and challenges in sustainable food production and the bioeconomy (Lammie & Hughes, 2016; Mantegazza et al., 2023). Additionally, there are clear links between the emergence of new antimicrobial resistant microbes and climate change as higher temperatures are associated with higher bacterial growth rates, increased gene transfer, and the emergence of new pathogens (Kaba et al., 2020). Addressing AMR requires a One Health approach, integrating human, animal, and environmental health strategies to reduce the overuse of antimicrobials and promote responsible stewardship of microbial communities. Of note, this stewardship may also incorporate strategies of withholding effective novel oral antibiotics as a cost-effective measure to combat emerging pathogens as part of comprehensive pandemic preparedness programs (Megiddo et al., 2019). By preserving the health of microbes in the environment and reducing environmental contamination with antimicrobial resistant microbes, we can enhance ecosystem services and maintain the delicate balance necessary for sustainable living.

19.3.3 Healthy Plants

The significance of healthy plants in the Circular Bioeconomy is paramount, particularly through the lens of biodiversity and sustainable farming practices. Biodiversity fosters resilience in agroecosystems, allowing for a more robust response to pests, diseases, and changing climate conditions (Francis, 2019). Polyculture and crop rotation can mitigate soil depletion and increase nutrient availability, ultimately leading to healthier and more secure food systems. Sustainable practices like agroecology and permaculture not only enhance plant health but also support a diverse range of species, creating a more interconnected ecosystem (Francis, 2019). By prioritizing the cultivation of diverse plant species, we can improve yields and nutritional quality while simultaneously reducing the ecological footprint of agricultural practices (Francis, 2019). Additionally, through the prioritization of sustainable farming practices, waste reduction, and a circular approach to production, plants can be used as the raw materials, sources of bioenergy, biopesticides, and organic fertilizers in the Circular Bioeconomy model (Chap. 7—Danies).

19.3.4 Healthy Animals

Healthy animals play a crucial role in a circular bioeconomy, acting as both contributors to and beneficiaries of sustainable systems. Livestock can enhance soil health through managed grazing practices, which stimulate plant growth and carbon sequestration (Teague & Kreuter, 2020). Furthermore, animals can be integrated into diverse farming systems, where they contribute to nutrient cycling and pest control (Teague & Kreuter, 2020). Insects have been detailed here (Chap. 12—Tomberlin) as an important animal component of successful Circular Bioeconomies. By diversifying agriculture, digesting food waste, contributing to the production of biofuels and biofertilizer, and serving as sources of natural products (antimicrobial peptides, anticancer compounds, and chitin), they play an integral role in ecosystem circularity. However, the health of animals is often tied to the health of their environments, emphasizing the importance of ethical and sustainable animal husbandry practices and a commitment to environmental protection. A One Health approach recognizes the interconnectedness of animal health, environmental health, and human health, making it imperative to implement strategies that support animal welfare while also enhancing the stability and productivity of the bioeconomy.

19.3.5 Healthy Humans

Lastly, the well-being of humans is a fundamental component of the Circular Bioeconomy. Addressing health disparities and food insecurity in disadvantaged communities is essential for creating an equitable food system (Chap. 13—Hochman). A One Health approach highlights the importance of ensuring access to nutritious food and the ability to make informed, culturally relevant dietary choices (i.e., "food sovereignty") (Patel, 2009). Community gardens, urban agriculture, and local food systems can empower individuals, promote food sovereignty, and foster resilience against economic fluctuations. By focusing on inclusive policies that consider the social determinants of health, we can ensure that all populations can benefit from and contribute to a sustainable and circular bioeconomy, further fostering a healthy global population.

19.4 Threats to Health in the Circular Bioeconomy

19.4.1 Climate Change

Climate change poses a significant threat to the health of ecosystems and the viability of a circular bioeconomy. Extreme weather events, such as floods, droughts, and hurricanes, disrupt natural systems and can lead to significant agricultural losses. These disruptions not only impact food production but also strain resources necessary for maintaining healthy soils and clean water. Resilient ecosystems, therefore, become paramount; they provide natural buffers against climate extremes and help stabilize local climates. Strategies like restoring wetlands, reforesting degraded areas, and implementing integrated water management can enhance ecosystem resilience and mitigate the impacts of climate change on the bioeconomy (Chap. 13—Hochman) (Hutton et al., 2007; Maltby & Acreman, 2011; Locatelli et al., 2015).

19.4.2 Urbanization and Land Use

Land use is another critical threat to health within a circular bioeconomy (Chap. 17—Ventura). The conversion of natural habitats into agricultural or urban areas often leads to habitat fragmentation and loss of biodiversity. Preserving and connecting "wild" habitats is vital for promoting genetic diversity and ecosystem health. These areas serve as refuges for wildlife, help maintain ecological processes, and provide critical agricultural services such as pollination and pest control (Holland et al., 2017). By prioritizing land-use policies that protect existing ecosystems and promote sustainable land management practices, we can enhance biodiversity and ensure the successful sustainability of the bioeconomy.

19.4.3 Pollution and Environmental Contaminants

Widespread pollution and environmental contaminants—such as plastics, agrochemicals, and industrial waste—pose serious risks to microbes, plants, animals, and humans (Chap. 16—McKinney). These pollutants can disrupt endocrine systems, reduce biodiversity, and compromise food safety. For example, pesticide runoff can contaminate water supplies, harming aquatic life and entering the human food chain (Shefali et al., 2021). Addressing pollution requires comprehensive strategies, including stricter regulations on chemical use, investment in clean technologies, and community education on waste management. By tackling pollution at its source through a variety of strategies and mechanisms of the circular bioeconomy, we can protect the health of ecosystems and create a safer, more sustainable environment for all.

19.5 Future Solutions

19.5.1 Technological Advancements

Advancements in renewable energy sources, energy storage solutions, carbon capture, precision agriculture, green infrastructures, transportation, and bioinformatics have all significantly contributed to the mitigation of climate-related challenges to the Circular Bioeconomy. Climate smart technologies contribute to climate resilience through a reduction in greenhouse gas emissions, an increase in soil carbon sequestration, and a promotion of sustainable practices (Chap. 10—Zilberman). Technological advancements at the food-energy-water nexus have underscored mechanisms of circular practices that reduce, recycle, and reuse waste, thus making it possible to ensure productivity and profitability within a sustainable system. These technologies have provided tools to address growing populations and food insecurity needs while minimizing environmental impacts and preserving biodiverse ecosystems. The challenges that remain are effectively implementing and scaling up the use of these technologies across diverse production systems.

19.5.2 Implementing Sustainable Practices

Implementing sustainable practices within the Circular Bioeconomy begins with emphasizing the use of renewable capital and resources. This involves transitioning from finite resources to those that can be replenished naturally, such as solar energy, wind power, and sustainably harvested materials. By adopting renewable energy sources, businesses can significantly reduce their carbon footprint and minimize reliance on fossil fuels. Additionally, promoting practices such as regenerative

agriculture and no-till practices helps maintain soil health and biodiversity while ensuring that natural ecosystems are preserved (Chap. 7—Danies) (Francis, 2019). The use of organic fertilizers, cover cropping, and agroforestry not only enriches the soil but also supports the microbial communities essential for nutrient cycling (Prasad et al., 2021). This interconnected approach nurtures the environment and creates a resilient agricultural system that can sustain plant, animal, and human health.

Minimizing waste is another critical component of a circular bioeconomy that directly impacts the health of the planet. This can be achieved through practices like recycling, composting, and the development of closed-loop systems where by-products are repurposed into new resources. For example, organic waste can be composted to enrich soil and support plant growth, while by-products from agricultural processes can be converted into bioenergy (Reid et al., 2020). Ensuring that all aspects of production and consumption prioritize the health of the environment, microbes, plants, animals, and humans is essential for a holistic approach. Education and collaboration among stakeholders, including policymakers, businesses, and communities, are vital to fostering sustainable practices that promote health and resilience across all levels of the bioeconomy. This requires both bottom-up, community-centric and top-down, policy-centric approaches. By creating frameworks that value ecological balance and resource efficiency, we can build a sustainable future that supports both the health of people and the planet.

19.5.3 Bottom-up Approaches: Community Empowerment

Communities are intimately connected to and thus have a deep understanding of their natural resources, cultural practices, and the socioeconomic context of their conditions. Through community member empowerment and participation, Circular Bioeconomy principles can be tailored to local materials and ecosystems, minimizing waste and maximizing efficient and effective implementation. This type of stakeholder engagement can foster transparency and trust while providing with communities a sense of ownership, thus increasing the likelihood of adaptability and behavioral change. Furthermore, community-led initiatives ensure economic benefits remain within the community, are distributed equitably (including to marginalized groups), and reduce inequality through capacity building.

The example of Regional Consortiums of Agricultural Experimentation (CREA) (Chap. 26—Esteban) represents community-centric initiatives poised to overcome implementation challenges associated with the establishment of the Circular Bioeconomy. The decentralization of research and implementation units and the establishment of community leaders can effectively demonstrate the feasibility of adopting novel production strategies and schemes. These strategies, which are specifically adapted to local market conditions and solve a specific production problem, can demonstrate the applicability of Circular Bioeconomy practices on a local scale. Decentralization often allows for more effective and less resource-intensive waste management and reduced transportation footprints, aligning with Circular

Bioeconomy goals. Furthermore, creating "horizontal protagonism" and bridging the disconnect between rural and urban communities are crucial steps in closing the waste-to-resource loop within the Circular Bioeconomy framework. Community feedback through these decentralized units can inform policy to reflect local priorities and realities, as well as hold governing bodies accountable through program evaluation.

19.5.4 Top-down Approaches: Policy Generation

Although bottom-up approaches have obvious benefits to circularity implementation at the local level, top-down approaches can be equally effective and complementary. A top-down approach often establishes coherent frameworks with unified objectives, vision, and actions. Consistency across agencies often promotes alignment of the Circular Bioeconomy with broader, global goals like climate change mitigation, biodiversity conservation, and sustainable development. This consistency, in turn, allows for more effective regulation and compliance enforcement, leading to a larger impact on waste reduction and renewable resource utilization. Policies can also encourage adoption of sustainable practices and engagement in the Circular Bioeconomy through subsidies, tax breaks, and other incentives (like the Policy for Minimum Price Guarantees for Sociobiodiversity Products (PGPMBio) discussed in Chap. 25—Paes). In a top-down approach, resources can be effectively and equitably allocated for research, innovation, and infrastructure necessary for the establishment of the Circular Bioeconomy across various regions and social groups. Further, policymakers can create opportunities for broad collaboration across industry, research institutions, and communities, ensuring diverse stakeholder involvement.

Top-down approaches can enable the development of large-scale systems, help commercialize and scale emerging technologies, and promote these technologies in the global market, driving demand and investment opportunities. Also, consistent standards and centralized oversight can aid in monitoring progress and profitability, as well as evaluate the effectiveness and broad impacts of circular processes. Lastly, top-down approaches can effectively create capacity for rapid response and resiliency in the face of environmental/climate crises and economic downturns by enabling swift policy adjustments to maintain progress toward Circular Bioeconomy goals.

It should be noted that models of collaboration between governments (top-down) and grassroots organizations (bottom-up), such as the sociobioeconomy (SBE) model presented in Chap. 25—Paes and Chap. 27—Dürr, can be especially useful in promoting public policies that address the goals of the Circular Bioeconomy (including the promotion of non-timber forest products) while protecting the rights of Indigenous peoples and safeguarding environmental biodiversity. These models can reconcile supply chains and "value chains," provide equitable economic

opportunities, combat predatory activities, and preserve ecosystems that support local economies.

19.6 Training the Workforce

Workforce capacity building and training are crucial in a One Health approach to establishing the Circular Bioeconomy because they equip professionals across disciplines with the knowledge and skills needed to address the complex challenges mentioned in this text. The Circular Bioeconomy relies on the efficient and sustainable use of biological resources, which requires expertise in areas such as agriculture, environmental science, public health, veterinary medicine, and industrial processes, while a One Health perspective emphasizes the interdependence of human, animal, and environmental health, making cross-disciplinary collaboration essential. Training programs can foster systems thinking, enhance technical competencies, and promote innovative problem-solving strategies, enabling individuals (in both professional and community spaces) to implement solutions that reduce waste, enhance resource efficiency, and improve ecological resilience. By investing in workforce development, stakeholders can ensure that the Circular Bioeconomy is not only scientifically sound and operationally effective but also inclusive and equitable, benefiting diverse populations and ecosystems globally. We advocate for educational and workforce investment from an early age to more effectively foster this type of panoramic, transdisciplinary thinking. Below, we discuss ways in which One Health principles can be disseminated at various educational strata.

19.6.1 K-12 Programs

Integrating One Health principles into educational frameworks is vital for cultivating a holistic understanding of the interconnectedness of human, animal, plant, and environmental health. By embedding One Health concepts across all educational levels, students can gain a comprehensive perspective on complex health issues and be better prepared to develop effective solutions. However, implementing a One Health approach necessitates knowledge-based skills, making it crucial to foster transdisciplinary literacy and teamwork from an early age. Engaging K-12 students with topics like biodiversity, ecosystem services, climate change, and the roles these play in the Circular Bioeconomy can stimulate critical thinking and problem-solving abilities. By incorporating One Health into early education, students cultivate a sense of responsibility and stewardship for the planet and its inhabitants, recognizing how human activities impact ecosystems and biodiversity, as well as how environmental health reciprocally influences human and animal well-being (key concepts in the Circular Bioeconomy). Integrating environmental education into early learning fosters an appreciation for the interconnectedness of food systems,

energy use, and water resources, laying a solid foundation for understanding more complex concepts, including the application of a One Health approach to the Circular Bioeconomy, as they progress in their education and future careers.

19.6.2 Collegiate Level Training

Training undergraduates in One Health is essential to advancing Circular Bioeconomy goals globally because it instills interdisciplinary thinking and sustainability principles early in their academic and professional journeys. By exposing undergraduates to diverse interests to this integrative framework, they develop a systems-thinking mindset, critical for addressing global challenges such as climate change, biodiversity loss, and resource scarcity. Undergraduate education in One Health equips future professionals with the tools to innovate sustainable solutions, advocate for policies that balance economic growth with environmental stewardship, and collaborate across sectors and disciplines. Furthermore, a well-trained undergraduate workforce ensures a pipeline of knowledgeable leaders who can champion Circular Bioeconomy principles globally, fostering inclusive and resilient systems that benefit both society and the planet.

19.6.3 Post-Baccalaureate Training

Post-baccalaureate training in One Health provides advanced, specialized education that equips professionals with the interdisciplinary expertise needed to address complex challenges at the interface of human, animal, and environmental health. Unlike undergraduate training, post-baccalaureate programs focus on applied skills, research, and policy development, enabling participants to translate theoretical knowledge into practical solutions utilizing their expertise. One Health programs designed for professionals can foster cross-sectoral collaboration, systems thinking, and leadership skills, which are essential for implementing sustainable strategies in the Circular Bioeconomy more broadly. Additionally, post-baccalaureate training ensures that professionals from diverse fields—such as nursing, veterinary medicine, human medicine, environmental science, and public health—are equipped to work together, driving global efforts to reduce waste, promote renewable resources, enhance ecological resilience, and align policies with local cultures and regulatory frameworks. This advanced education builds a workforce capable of leading transformative changes, ensuring the circular bioeconomy is both effective and inclusive on a global scale.

Regardless of their educational or career stage, One Health training is vital for addressing the world's most complex challenges, including the widespread integration of Circular Bioeconomies. By providing accessible and broadly relevant education and ongoing training in the One Health approach, we can better equip individuals

to confront the persistent (and emerging) challenges facing our planet today. Furthermore, emphasizing the interdependence of human, animal, plant, and environmental health, especially at the food-energy-water nexus, can inspire educational initiatives that motivate individuals to adopt sustainable practices and advocate for policies that enhance global health.

19.7 Conclusion

The One Health approach amplifies the importance of the Circular Bioeconomy by highlighting how the health of humans, animals, plants, and the environment are intricately linked to its objectives: resource efficiency through reducing environmental pressures that threaten health; biodiversity preservation through maintaining ecosystem health and bioeconomy supply chains; sustainable agriculture to create resilient and healthy food systems; and interdisciplinary research to foster novel solutions through collaboration. To effectively and sustainably build and maintain Circular Bioeconomies globally, it is imperative to focus on the impacts on planetary health. Addressing the threats of climate change, alterations in land use, and the increased levels of environmental contaminants requires the involvement of stakeholders through both bottom-up, community-centric and top-down, policy-centric approaches. These methodologies foster technological innovation, incentivize sustainable process implementation, and can help monitor the successes and failures of new strategies. By training the workforce in the One Health approach, including exposure to concepts at early learning stages, we can build the infrastructure of systematic thinking necessary to encourage the broad adoption of Circular Bioeconomy principles.

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Chapter 20
Amplifying a Macroalgae Bioeconomy

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20.1 Introduction

The convergence of breakthroughs in DNA research, advances in biotechnology, and emerging remote-control capabilities, alongside mounting global challenges such as climate change, food security, rural development, and biodiversity preservation, has led to the rise of the bioeconomy. This new economic model leverages modern technologies and natural resources to produce sustainable sources of food, energy, chemicals, and carbon sequestration (Zilberman, Chap. 1). While the bioeconomy spans multiple sectors, one of the most promising yet underutilized areas is the blue bioeconomy—centered on aquatic resources. Beyond the well-established global fishery industry, a growing focus is emerging around macroalgae and microalgae (Hochman & Palatnik, 2022). The macroalgae (seaweed) sector generates between $12 and 17 billion annually, yet its full potential to address pressing global needs remains largely untapped. This chapter provides an overview of the status of

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the macroalgae sector, recent developments, and a forward-looking agenda to scale its economic and environmental contributions—drawing in part from presentations at the inaugural meeting of the International Bioeconomy & Macroalgae Center (IBMC).

The first section overviews the current activities and economics of the macroalgae sector, highlighting new capabilities and opportunities for expansion. The second section addresses key challenges in upscaling the industry at different stages of the supply chain, including growing macroalgae feedstocks, processing them into a variety of commodities, including high-value chemicals, and marketing final products. It also profiles emerging enterprises that may play a pivotal role in expanding the industry sector. The third section outlines some of the constraints that are likely to prevent the macroalgae sector from reaching its potential. The final section concludes by offering some solutions to these constraints and outlining a strategic vision for a community of researchers and practitioners to advance the macroalgae bioeconomy.

20.2 The Current Situation of the Macroalgae Sector

According to multiple sources[1,2] the global commercial seaweed sector size was $17 billion in 2023 and is projected to grow to $35 billion by 2032, growing at a rate of about 8.2%. The World Bank estimates that the industry will grow by $12 billion by 2030 by expanding into new seaweed product markets. Altogether, these projections indicate strong growth of the macroalgae industry.

According to Zhang et al. (2022), between 2000 and 2020, Asia accounted for 97% of global seaweed production, with China alone contributing 57%, followed by Indonesia (27%), Korea (5%), the Philippines (4%), Taiwan (1.6%), and Japan (1.15%). In comparison, the Americas produced just 1.36%—led by Chile (1.2%), with Canada and the USA contributing only 0.04% and 0.02%, respectively. Europe represented just 0.80% of global production, with Norway at 0.46%, France at 0.14%, and Ireland at 0.08%. This highlights a stark geographic imbalance, with Asia dominating seaweed production. However, demand is rising globally. In the USA, for instance, seaweed consumption is projected to reach $1.5 billion by 2032—driven in part by increasing consumer interest and enthusiasm around seaweed's potential for food, health, and sustainability.

There are many current, and many more potential, uses of macroalgae. The largest current application is in the food and beverage industry (Hochman & Palatnik, 2022). Some algae, such as nori and wakame, are consumed directly, while others are processed as food additives. The market for algae-based products intended for human consumption was valued at $5.3 billion in 2023 and is projected to grow to

[1] https://www.fortunebusinessinsights.com/industry-reports/commercial-seaweed-market-100077. May 13, 2025

[2] https://unctad.org/system/files/official-document/ditcted2024d1_en.pdf. May 13, 2025.

$7.3 billion by 2028. The second major use of macroalgae is in the production of hydrocolloids (gums), where the extraction of alginate, carrageenan, and agar is used to produce gelling, thickening, and stabilizing agents.[3] The agar market is estimated to be between $300–$400 million,[4] carrageenan between $850 million-$1 billion,[5] and alginate between $700–$900 million.[6,7] Agar is commonly used as a gelling agent in processed foods and plays an important role in microbiological and plant tissue cultures. Carrageenan is utilized for stabilizing dairy products, processed meats, toothpaste, and cosmetics. Alginate serves as a thickener, stabilizer, emulsifier, and gelling agent in food products, with additional applications in pharmaceuticals, cosmetics, and wound care. There is a growing demand for algae to produce these materials, causing overharvesting of wild reserves, especially in Morocco and Chile. A derivative of agar is agarose, which is used in DNA electrophoresis, chromatography, cell culture, tissue engineering, and the food industry.[8] The raw agarose market is estimated at $250 million in 2023, expanding to $450 million by 2031,[9] and the agarose resin is valued at approximately $1.7 billion in 2023, with projections estimating growth to $3.9 billion by 2033, reflecting a Compound Annual Growth Rate (CAGR) of 8.6%.[10] The commercial use of agar and agarose highlights the untapped potential for growth within the macroalgae sector—particularly in the development of high-value derivative products. These polysaccharides, widely used in food, biotechnology, and research, exemplify how specific compounds from macroalgae can support diverse industrial markets. Beyond agar-based applications, macroalgae are increasingly being explored as sustainable raw materials in agriculture (e.g., biostimulants and soil conditioners), construction (e.g., bio-based insulation and composite materials), pharmaceuticals (e.g., anti-inflammatory and antiviral compounds), biofuels (as a source of third-generation feedstocks), textiles (e.g., biodegradable fibers), and bioplastics (e.g., seaweed-based packaging). Additionally, macroalgae offer promising

[3] https://www.marketsandmarkets.com/Market-Reports/algae-product-market-250538721.html#:~:text=The%20algae%20products%20market%20size,functional%20foods%2C%20and%20nutraceuticals.

[4] https://www.skyquestt.com/report/agar-market#:~:text=Global%20Agar%20Market%20size%20was,are%20helping%20boost%20agar%20sales.

[5] https://www.grandviewresearch.com/industry-analysis/carrageenan-market#:~:text=The%20global%20carrageenan%20market%20size%20was%20estimated%20at%20USD%20871.66,USD%201%2C324.62%20million%20by%202,030.

[6] https://www.grandviewresearch.com/industry-analysis/alginate-market#:~:text=Alginates%20have%20an%20industrial%20application,to%20drive%20the%20segment%20growth.

[7] https://www.precedenceresearch.com/alginate-market

[8] https://www.sigmaaldrich.com/US/en/products/chemistry-and-biochemicals/biochemicals/agarose#:~:text=Agarose%20is%20non%2Dtoxic%20and,chromatography%2C%20affinity%20chromatography%2C%20and%20ion

[9] https://www.marketresearchintellect.com/product/global-agarose-market-size-and-forecast/?utm_source=chatgpt.com/

[10] https://www.factmr.com/report/5239/agarose-resin-market?utm_source=chatgpt.com

solutions in environmental applications such as carbon capture, nutrient remediation, and habitat restoration.

Algae are generally classified into three main groups: green algae (Chlorophyta), brown algae (Phaeophyta), and red algae (Rhodophyta).[11,12] They grow in a wide range of environments, including oceans, lakes, rivers, and even snow. Green Algae (Chlorophyta) are the most diverse, including both single-celled and multicelled forms. They are commonly found in freshwater and marine environments.[13] Examples include Chlamydomonas, Ulva (sea lettuce), and Spirogyra. Brown Algae (Phaeophyta) are characterized by their brown color, are mostly marine, and are found in colder waters. They include large seaweeds like Macrocystis (giant kelp) and Sargassum.[14] Red Algae (Rhodophyta) are also primarily marine and are known for their red or reddish-brown color. Examples include Porphyra (nori or laver) and Gelidium.[15] According to Guiry (2024), an estimated 72,500 species of algae have been documented, including approximately 22,000 green,[16] 7000 red,[17] and 2000 brown algae.[18] While algae span many additional taxonomic categories, only about 50 species are currently being commercially utilized.[19]

While wild harvesting remains common, much of today's macroalgae cultivation still relies on traditional methods and technologies (Fernand et al., 2017). However, there is growing evidence that the seaweed industry could scale significantly through the adoption of innovative and emerging technologies—opening the door to a wider range of feedstocks and high-value applications (Chemodanov et al., 2019). Two key forces driving this expansion are the urgent need to address climate change and the global transition toward alternative energy sources, sustainable materials, and scalable carbon sequestration solutions.

Advances in scientific and technological capabilities including genomics and biotechnology, more powerful computing (digital twins and artificial intelligence), and monitoring technologies (such as drones) are enabling new uses of seaweeds through improved and diversified processing capacities. These technologies, like

[11] https://pmc.ncbi.nlm.nih.gov/articles/PMC5447909/

[12] https://www.futuremarketinsights.com/reports/algae-based-supplement-market#:~:text=As%20the%20demand%20for%20plant%2Dbased%20and%20sustainable,pool%20of%20wellness%2Dminded%20consumers%20around%20the%20world.

[13] https://www.lenntech.com/eutrophication-water-bodies/algae.htm#:~:text=Chlorophyta:%20division%20of%20the%20kingdom%20of%20protista,or%20marine%2C%20a%20few%20types%20are%20terrestrial

[14] https://en.wikipedia.org/wiki/Brown_algae

[15] https://www.thoughtco.com/major-types-of-algae-373409#:~:text=These%20protists%20can%20be%20categorized,Roland%20Birke/Photolibrary/Getty%20Images

[16] https://en.wikipedia.org/wiki/Green_algae

[17] https://en.wikipedia.org/wiki/Red_algae#:~:text=Eukaryote%20§%20Phylogeny-,Species%20of%20red%20algae,Vertebrata%20simulans

[18] https://en.wikipedia.org/wiki/Brown_algae#:~:text=Between%201%2C500%20and%202%2C000%20species,environmental%20significance%20through%20carbon%20fixation.

[19] https://onlinelibrary.wiley.com/doi/10.1111/jpy.13431#:~:text=ACKNOWLEDGMENTS-,Abstract,14%20phyla%2C%20and%2063%20classes.

digital twins, simulate the behavior of algae and their interactions with the environment to optimize their production, and technologies that enhance monitoring of and access to algae can provide precision farming. Genetic engineering techniques offer the potential to develop new macroalgae strains with enhanced or tailored traits for specific applications. In parallel, advances in cultivation and harvesting technologies—such as direct seeding methods, multiplexed automated harvesting systems, and efficient dewatering techniques (e.g., high-voltage, short-pulsed electric fields (Steinbruch et al., 2024))—can significantly improve the efficiency and scalability of both biomass production and downstream processing (Prabhu et al., 2020).

There are several applications of algae that have immense potential, for example, in crop and animal agriculture. Algae can be used as biofertilizers, soil conditioners, and animal feed supplements. Notably, certain red macroalgae like *Asparagopsis taxiformis* can reduce methane emissions in ruminants by up to 98% when used as animal feed. As society becomes more willing to invest in carbon reduction strategies, the value of algae-based solutions for methane mitigation increases significantly.[20,21] There is a societal need for increased production of protein and nutrients, which can be met by algae production (Wells et al., 2017). Macroalgae are proven to be effective at stimulating plant growth through their use as biofertilizers, biostimulants, and growth-promoting hormones and can improve the productivity and reduce the waste of agricultural production (Ammar et al., 2022). Furthermore, as limitations become evident in relying solely on electricity for transportation, especially in aviation and marine sectors, there is a critical need for sustainable liquid fuels. Algae have a large potential to be a source for many of these fuels (Chaudry et al., 2025). Finally, algae have the capacity to sequester significant amounts of carbon—up to 1.8 tons of CO_2-equivalent per ton of biomass—positioning them as a promising tool for reducing atmospheric greenhouse gases (GHGs). The critical challenge lies in ensuring that this captured carbon is either securely stored in the ocean over the long term or converted into stable, durable materials. Although this approach remains scientifically and politically contentious, it is the focus of active research. If these challenges can be overcome, algae-based carbon sequestration could represent a transformative breakthrough in climate mitigation (Sarwer et al., 2022).

At present, our knowledge of macroalgae remains limited. We utilize a small number of species, and the technologies for both harvesting and processing are still underdeveloped and are reliant on manual labor. Despite this, there are many opportunities to expand macroalgae production and its products. Given the abundance of natural resources and the increasing demand for algae-derived products, the industry has the potential to grow far beyond current projections—provided there is strategic investment and supportive policy. With sustained investment in research and development, and more critically, in scaling up production infrastructure, the

[20] https://pmc.ncbi.nlm.nih.gov/articles/PMC10190624/#:~:text=Additionally%2C%20in%20March%202022%2C%20the,the%20production%20of%20ruminant%20protein.

[21] https://mostpolicyinitiative.org/science-note/seaweed-for-cattle-feed/#:~:text=Seaweed%20additives%20in%20cattle%20diets,2020;%20Roque%2C%202,019.

macroalgae industry could exceed expectations, growing not just twofold, but potentially reaching $100 billion—or even approaching $1 trillion—over the next 30 years. In the following section, we explore some of the key challenges that must be addressed to realize this potential.

20.3 The Challenge of Upscaling the Macroalgae Industry

The macroalgae industry is still largely dependent on traditional manual cultivation and harvesting approaches and focuses on a limited number of species. In developed countries, macroalgae production can be prohibitively expensive (Palatnik et al., 2023) and would benefit significantly from modernization. Although more than 11,000 macroalgae species have been identified (Stiger-Pouvreau & Zubia, 2020), just 12 species account for 95% of global commercial production.[22] This limited utilization—driven by a lack of knowledge about the vast majority of species—constrains the industry's full potential.

However, this underdevelopment, particularly outside of Asia, presents a major opportunity. Many regions can leapfrog outdated practices and directly adopt modern technologies, much like how mobile phones spread rapidly in Africa and South East Asia without the need for widespread landline cable phone infrastructure. Expanding and modernizing the macroalgae sector will require building both innovation and product supply chains (Zilberman, Chap. 1).

20.3.1 Innovation Supply Chain

The innovation supply chain aims to develop new knowledge that results in new product and process innovations. A critical first step is expanding the industry's foundational scientific understanding. This includes expanding our knowledge of its biodiversity, identifying species, documenting their genomes, and assessing their behavior and chemical properties. Currently, no global seaweed biobank exists to curate and preserve representative collections of living specimens from the world's diverse marine environments. As a result, the full breadth of seaweed biodiversity—and its immense potential for various applications—remains largely unknown and underexplored. This lack of a centralized repository not only limits our understanding of seaweed's genetic and ecological diversity but also leaves many species vulnerable to extinction amid escalating environmental stressors (Wade et al., 2020; McPherson et al., 2021; Saada et al., 2016). Without coordinated preservation efforts that capture the full spectrum of species, we risk losing valuable genetic resources that could hold keys to resilience, adaptability, and innovation.

[22] https://seaweedinsights.com/global-production/

Addressing this gap is a critical first step in strengthening the seaweed innovation supply chain, which depends on robust foundational scientific knowledge to drive new product and process development. Expanding our understanding of seaweed biodiversity—through species identification, genomic documentation, and assessments of behavior and chemical properties—is essential. Macroalgal germplasm banks, as advocated by Wade et al. (2020), are needed to preserve genetic diversity, support conservation, and provide a resource base for food security and industrial applications. Such efforts must be supported by coordinated international initiatives that protect marine algal species via germline preservation, the development of genetic tools for breeding, and comprehensive mapping of geographic and ecological distributions.

Recent discoveries, such as those by Stiger-Pouvreau and Zubia (2020), who identified over 2000 new macroalgal species around French Polynesia, underscore the vast and largely untapped biodiversity that exists. These reef macroalgae offer applications across sectors including food, health, cosmetics, agriculture, and environmental remediation. To fully realize this potential, the research community requires shared tools and platforms like PhycoCosm,[23] which hosts genomic data for over 100 algal species and enables exploration of gene functions, comparative genomics, and evolutionary relationships. Advancements in this foundational knowledge are essential not only to identify viable, marketable products but also to ensure complementary utilization of entire algal feedstocks and, critically, to preserve biodiversity as the industry scales.

A second stage of foundational research focuses on advancing the commercialization of the macroalgae sector through the development of biofoundries. These facilities will support breeding programs, enable genome editing, and facilitate microbiome analysis. Genetic improvement programs can lead to the development of seaweed strains that are more resilient to diseases and environmental stress, while requiring fewer resources for cultivation (Khan et al., 2024). Understanding the biochemical composition of various macroalgae—and how it changes under different environmental or processing conditions—is essential for identifying promising sources of high-value products. This knowledge also helps determine optimal conditions for achieving desirable traits, such as enhanced disease resistance or elevated concentrations of valuable compounds. To scale biomass production efficiently and cost-effectively in the face of ongoing climate change, research must focus on improving heat tolerance, maintaining high growth rates, increasing metabolite yields, and industrializing traits that add commercial value. These advancements are crucial for reducing vulnerability and unlocking the full potential of macroalgae as a sustainable bioresource.

Identifying different macroalgae species is only the starting point. Yield volatility is a major challenge. It is crucial to develop better knowledge about cultivation and harvesting. This includes optimizing farming systems, including automation and optimization of culture conditions, and harvesting strategies that can reduce labor costs and increase efficiency. Modernization can be expanded by the adoption of new

[23] https://jgi.doe.gov/user-science/science-stories/one-stop-shop-analyzing-algal-genomes-0?utm

management technologies, AI, and Digital Twins. Innovations in harvesting using boats and machinery (rakes and trawlers) allow collection of seaweed more efficiently while at the same time developing tools to minimize damage to the seabed and the environment (Khan et al., 2024; Hemavathy et al., 2025). Other tools such as screw press and pulsed electric fields will enable onsite dewatering and nutrient recycling, increasing efficiency and sustainability. Modular harvest systems, such as those currently produced by GreenWave, can facilitate the industry's expansion by enabling seaweed farmers to expand their production area with ease. Yet other technologies like drones, variable depth production systems, and fully automated harvest systems like the SeaCombine™ from Sea6 can increase productivity and improve resilience to variation in climate conditions. These innovations will be critical to transitioning seaweed farming into a modern, scalable, and environmentally responsible industry.

Macroalgae can be cultivated in both ocean-based and land-based systems, each offering distinct advantages and challenges. Ocean cultivation does not compete with arable land, can utilize nutrient-rich waters, and holds significant potential for large-scale expansion. However, it also presents major operational hurdles: yields can fluctuate due to environmental variability, temperature control is difficult, and substantial infrastructure is required to withstand wave action, storms, and corrosion. Moreover, large-scale ocean farming may carry ecological risks for marine ecosystems.

In contrast, land-based cultivation offers more precise control over environmental conditions, enabling optimized growth, efficient biomass extraction, and consistent year-round production. This approach can lead to higher yields and more reliable product quality. Notable examples include Arcadia Seaplants in Nova Scotia and Oregon Seaweed in North America, both of which have established land-based farms that grow a range of seaweed food products such as Pacific dulse—a red seaweed valued for its nutritional content and distinctive flavor—in seawater ponds. These controlled environments allow for fine-tuned management of cultivation variables. However, land-based systems are energy-intensive and currently face scalability limitations.

Once seaweed is produced, it must be processed and converted into valuable products, which requires developing and expanding the capacity of biorefineries using different approaches, including hydrothermal treatment, fermentation, anaerobic digestion, green solvents, thermochemical methods, enzymatic hydrolysis, and more (Filote et al., 2021; Golberg et al., 2021). Biorefining technologies and management systems would aim to increase the number of valuable materials produced from algae, reduce waste, and treat it in a way that is not harmful to the environment. Production systems should be efficient and aim to reduce GHG emissions and other negative side effects, and the system design will emphasize profitability both in the short and long run. The design of biorefinery production and processing systems should be adapted to different biophysical and socioeconomic conditions and based on easily communicable and implementable principles (Khan et al., 2024).[24]

[24] https://www.fisheries.noaa.gov/national/aquaculture/seaweed-aquaculture

One promising supply chain of macroalgae co-produces seaweed and seafood. These systems are also known as integrated multi-trophic aquaculture (IMTA)—an approach that can increase efficiency, improve sustainability, and reduce environmental impacts in aquaculture systems. Co-production systems have symbiotic production of fish (e.g., salmon, seabass), shellfish (e.g., mussels, oysters, scallops), and crustaceans (e.g., shrimp, crabs) with seaweed. It is done in marine coastal farms, offshore systems, and land-based tanks. Seaweeds act as biofilters, absorbing excess nutrients (especially nitrogen and phosphorus) from fish or shrimp waste. China has large-scale systems of kelp and scallops or abalone; Norway and Canada co-culture Atlantic salmon with edible kelp (wakame); and in Chile, *Gracilaria* seaweed is co-cultured with mussels and sea urchins (Khan et al., 2024).

Another element of research that is needed prior to developing new supply chains and product markets is knowledge of the economics of production and demand for different by-products of macroalgae, as well as the institutional and economic challenges associated with establishing supply chains for macroalgae products. Macroalgae production systems will be diverse, depending on different conditions. They will be more expensive and mechanized in developed and developing countries (Palatnik et al., 2023). Research needs to consider different designs based on different conditions. A key concern is that new macroalgae production and processing may require new regulatory regimes and thus research that provides some foundation for this regime will be valuable. Reducing uncertainty about regulatory conditions can accelerate the emergence of the industry (Zilberman et al., 2022).

There are different kinds of innovation supply chains. Some are based on university research and technology transfer from the public to the private sector, and some take advantage of existing scientific knowledge or improve the production of feedstock or final products. Government initiatives, in terms of developing public goods and infrastructure, enable innovation systems (Zilberman, Chap. 1). Thus, investment in the innovation supply chain will require investment in universities, research institutes, and avenues for public and private collaboration.

20.3.2 Product Supply Chain

Product supply chains are used to implement innovations. The relationship between innovation and product supply chains is symbiotic; companies that implement innovations may have research departments that improve them (Reardon, 2025). Product supply chains consist of multiple elements. First are the hatcheries that provide the cultivars to the farmers. Then, units that grow and harvest seaweed. Third are units that provide inputs for production and harvesting, including pest control. Another element of the product supply chain is the transport of different intermediary products. This is followed by units that process the seaweed feedstock—currently most units are specialized in one product. The industry should strive to introduce multiple by-products, and then there is a distribution network including wholesalers and retailers. One of the big challenges in the design of the product supply chain is

determining the extent to which it will be vertically integrated or broken down into individual firms.

The exact structure of the supply chain depends on the features of the product and the availability of credit and resources. Supply chain design also depends on risk considerations and relative advantage. Some processors may not have a relative advantage or resources to produce seaweed, and therefore buy from, or contract with farmers. On the other hand, some processors might seek quality control and reliability of supply choosing instead to be vertically integrated in both production and processing of the product (Du et al., 2016). When seaweed is used for relatively high-value and quality products, it must be dried and processed quickly due to its limited shelf life. As a result, Japanese seaweed farmers often sell dried seaweed, particularly for nori (used in sushi), while many Korean seaweed farmers sell wet seaweed.[25,26] One example of a vertically integrated macroalgae firm is Ocean's Balance, an employee-owned company that farms and sustainably wild-harvests several seaweed species. They process these seaweeds into a variety of products, including dried seaweed, seasoning blends, and pasta sauces.[27] Another company is Cascadia Seaweed, a leading vertically integrated seaweed farming and bioprocessing company in North America that produces biostimulants for crops to promote growth, improve stress resistance, and reduce fertilizer use.[28]

20.4 Circularity and Socioeconomic Considerations

One of the challenges of designing production systems is to ensure that they contribute to overall social welfare, by addressing both economic and environmental implications. Environmental regulation should provide the incentive to develop circular systems, where some of the residues from algae production can be reused or converted to inputs for other production systems. Residues from algae production, especially in the ocean, can cause harm and that must be minimized, or better yet, eliminated. On the other hand, algae production can be used as a mechanism to

[25] https://seaweedinsights.com/sales-pyropia/

[26] https://www.sciencefriday.com/articles/seaweed-farming-slime-ruth-kassinger/#:~:text=Also%20relevant%2C%20the%20life%20of,%2C%20I%20couldn%27 t%20resist.

[27] https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.seaweedcouncil.org/maine-seaweed-companies/%23:~:text%3DOcean%27s%2520Balance%2520is%2520an%2520employee,oceansbalance.com%2520for%2520more%2520information.&ved = 2ahUKEwjM0MDd0qiNAxWUJEQIHZxsIoUQ-tANegQICRAe&usg = AOvVaw1cwW3qedhK2TmvPXdzXsij

[28] https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://uplink.weforum.org/uplink/s/uplink-contribution/a012o00001OSlBmAAL/regenerative-seaweed-for-sustainable-agriculture%23:~:text%3DCascadia%2520Seaweed%2520is%2520tackling%2520two,government%2520grant%2520funding%2520in%2520place.&ved = 2ahUKEwjM0MDd0qiNAxWUJEQIHZxsIoUQ-tANegQICRAY&usg = AOvVaw1D4yOAywUKF6YuIcfpRalb

improve water quality and reduce waste. Algae production may use residues from other industries, such as excess nitrogen from agriculture, as input for producing algae products. For example, there is evidence that macroalgae can be used with fish and animal waste to produce biogas (Barbot et al., 2016). A supply chain that uses the entirety of the seaweed feedstock and incorporates markets for seaweeds of different qualities and nutrient compositions is pivotal to the circular economy. However, designing these supply chains is challenging—not all seaweed-derived products will have similar demands, so even if two products are complementary in production, uneven demand for their applications can lead to waste in the system.

There are many socioeconomic considerations relevant to expanding the seaweed sector. A key stakeholder in the Americas and elsewhere is First Nations; many First Nations in the Americas and elsewhere have used macroalgae as a source of food and other products for a long time. They provide valuable knowledge for the development of new algae systems and can benefit from some of the new opportunities that algae production provides. Designing supply chains that engage First Nations has to take into account both their political situation and cultural sensitivity. There are several examples of collaboration between Indigenous people and governments in developing and modernizing seaweed farming. This direction has significant potential (Nor et al., 2017).

20.5 Constraints on the Establishment of a Macroalgae Sector

As noted earlier, developing new industries requires both research capacity and supportive regulatory frameworks. While the USA and other countries have a very strong emphasis on traditional agriculture and major commodity crops, research on aquaculture and macroalgae has been comparatively limited. Agricultural research, especially related to staple crops, receives significantly more funding than macroalgae research. For example, in 2024, the USDA's Agriculture and Food Research Initiative (AFRI)[29] had a budget of $445.2 million, primarily directed toward traditional agricultural systems. In contrast, funding for macroalgae research, while increasing, remains relatively low. Macroalgae research requires access to bodies of water and use of marine technologies, which haven't received the support that large agricultural experiment centers have received. For example, ARPA-E, a branch of the Department of Energy, has funded several macroalgae projects, such as the MARINER[30] program with $22 million, but this is considerably less than the funding allocated to traditional agriculture. Furthermore, there is limited infrastructure for research on macroalgae.

[29] https://www.nifa.usda.gov/grants/programs/agriculture-food-research-initiative

[30] https://arpa-e.energy.gov/programs-and-initiatives/view-all-programs/mariner#:~:text=The%20Department%20of%20Energy%20today,crops%20for%20land%20and%20water.

The situation in the EU is slightly better. European partnerships for agroecology and animal health and welfare are expected to receive €600 million. The European Commission allocated €220 million for aquaculture research for a few years.[31,32] The European Commission also created InvestEU Blue Economy, a large-scale equity fund, mobilizing €500 million in EU funds between 2021–2027, potentially resulting in up to €1.5 billion of risk-finance for innovative and sustainable blue economy SMEs and start-ups. However, this initiative mostly emphasizes the production of fish, and macroalgae plays a minor role.[33]

Regulation can pose a major obstacle to the establishment of new algae industries. It is often inconsistent and spans multiple jurisdictions, leading to delays and uncertainty (Glass, 2015). Obtaining permits and licenses for algae production can be a lengthy and complex process. Licenses to start a new algae production facility in parts of the USA may take up to two and a half years, discouraging potential investors.[34] In addition to regulation and licensing of algae activities, algae production must comply with existing water, food, and feed regulations that can be complex and inconsistent among locations. In some cases, these regulations may address issues that are irrelevant to macroalgae production, further complicating compliance. All the regulatory demands and uncertainties increase both the perceived risk and financial burden of launching new seaweed ventures, limiting investment and slowing industry growth.

Another major constraint is the lack of familiarity among consumers—in Europe, the USA, Africa, and Latin America—with algae-based products. Zheng et al. (2024) suggest that much of the population in the USA has minimal awareness of macroalgae as a food source or of the various factors that determine its quality. They found that the demand and willingness to pay for macroalgae products depend on experience that most consumers in the USA lack. Thus, expanding the supply of macroalgae for food requires significant investment in education and exposure. At the same time, there is growing awareness of the environmental benefits of macroalgae, especially its ability to absorb carbon dioxide and remove excess nutrients from runoff, which protects marine ecosystems.[35] An increasing number of individuals are also recognizing the notion of circularity and the role macroalgae can play in it.

[31] https://www.eca.europa.eu/en/publications?ref=SR-2023-25#:~:text=II%20With%20support%20from%20the,economic%2C%20social%20and%20employment%20benefits.

[32] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/projects-details/43108390/101060607/HORIZON?isExactMatch=true&order=DESC&pageNumber=1&pageSize=50&sortBy=es_SortDate

[33] https://www.eca.europa.eu/en/publications?ref=SR-2023-25#:~:text=II%20With%20support%20from%20the,economic%2C%20social%20and%20employment%20benefits.

[34] This point was raised in the IMBC meeting, April second, 2025.

[35] https://www.aquariumofpacific.org/seafoodfuture/seaweed#:~:text=Seaweed%20plays%20many%20important%20roles,like%20oysters)%20from%20ocean%20acidification.

However, this is still a minority, and there is a need for significant educational efforts around the properties and values of macroalgae.[36]

Another constraint for the development of macroalgal industries is the reluctance of major agricultural, food, materials, and energy companies, especially in the West, to diversify their portfolio of raw materials beyond traditional centuries-old sources. The reason is clear—a lack of supply chains. Although carrageenan and agar are globally used, development of macroalgae feedstocks beyond these applications is slow. Materials like proteins, cellulose, salts, starch, and pigments from macroalgae have been produced in the lab, but they have not yet been made on a large scale. We believe major international ingredient companies, with their existing infrastructure and market reach, can significantly contribute to this effort.

Lack of financial resources is another constraint. Bankers and other sources of finance are often reluctant to lend to macroalgae ventures. Investors hesitate to support this emerging industry due to persistent technological hurdles, the lack of reliable infrastructure, and product demand.[37] The industry's short track record, unstable market conditions, and competition from established alternatives—coupled with high production costs and potential environmental risks—undermine profitability and dampen investor confidence.[38] Additionally, the sector's reliance on variable biophysical conditions and vulnerability to climate change contributes to the lack of finance for new algae projects. At the same time, convincing algae-based strategies that can address climate change have achieved significant support.

The challenges facing upscaling the macroalgae industry are similar to the ones facing the microalgae industry, in terms of limited finance, regulatory burden, and even monopolistic behavior of established alternatives. Yet there are evidence of a growing potential of algae to address major societal problems (Palatnik et al., 2025). The establishment of a strong bioeconomy will benefit from enhanced research, support to promising initiatives, and regulations that balance benefit and risk.

20.6 Conclusion

The macroalgae sector stands at a critical inflection point. It is anchored within the broader bioeconomy and offers a compelling blend of economic opportunity and environmental promise. With applications ranging from food and pharmaceuticals to renewable energy, animal feed, and carbon sequestration, macroalgae can contribute significantly to solving some of the world's most pressing

[36] https://www.1ocean.org/ocean-tales/the-importance-of-seaweed-a-cultural-and-environmental-shift#:~:text=Environmental%20and%20Economic%20Benefits%20of%20Algae&text=Seaweeds%20offer%20additional%20environmental%20benefits,of%20algae%20is%20equally%20significant.

[37] https://nph.onlinelibrary.wiley.com/doi/10.1111/nph.13278

[38] https://www.marketsandmarkets.com/Market-Reports/algae-product-market-250538721.html#:~:text=According%20to%20the%20CRN%27s%202021,infused%20nutraceuticals%20in%20the%20country.

challenges—climate change, food security, and rural development. Despite its vast potential, the sector remains underdeveloped outside Asia, constrained by limited research funding, regulatory hurdles, fragmented supply chains, and low consumer awareness. However, advances in biotechnology, digital tools, and genomics, coupled with growing demand for sustainable solutions, have created a strong foundation for expansion.

After decades of being seen as merely a "promising" feedstock, the macroalgae industry is finally experiencing a pivotal shift. For over half a century, macroalgae have been the subject of extensive academic research and ambitious private sector initiatives. Yet, these efforts have largely fallen short of catalyzing a transformation in the scale or economics of macroalgae production.

Today, however, a new driver is emerging. The recognition that macroalgae-derived biostimulants can significantly enhance conventional agriculture—particularly by improving crop resilience to heat waves—is generating renewed demand for macroalgal biomass. While the current enthusiasm surrounding biostimulants may not endure indefinitely, the demand surge offers a valuable opportunity. It could finally incentivize the long-needed investment in seaweed cultivation and harvesting technologies. Increased production activity would foster learning-by-doing, potentially reducing the cost of macroalgae cultivation. Beyond biostimulants, this development could unlock a cascade of co-benefits. Lower cultivation costs would support the viability of other high-value applications—such as extracting proteins for food and animal feed and biopolymers for compostable bioplastics production—thus broadening the economic foundation of the macroalgae sector.

Unlike the stable and controllable chemical processes that the algae-based bioeconomy seeks to replace, seaweed is a living organism whose growth and composition are inherently influenced by constantly shifting environmental conditions. These include long-term pressures like climate change and sudden disruptions such as seawater contamination from oil spills or other pollutants. As a result, the continuous interface between production and innovation supply chains is not merely beneficial—it is essential. The success and sustainability of macroalgae-based industries depend on an interdisciplinary approach. Biologists, environmental scientists, engineers, and economists must remain actively involved throughout the production supply chain, responding in real time to environmental feedback and technological advancements.

This kind of integrated collaboration ensures that seaweed cultivation systems can adapt effectively to emerging challenges, maintain ecological resilience, and continue to deliver on the promise of a sustainable, scalable bioeconomy. In contrast to traditional industrial models, the algae sector cannot afford to decouple innovation from implementation. Instead, it requires a living, learning network of stakeholders committed to long-term co-development. Coordinated efforts are needed to build robust innovation and product supply chains supported by targeted investments, enabling policies, and inclusive engagement with Indigenous communities and underrepresented regions. Regulatory reform and public education will reduce uncertainty and build a broader market base. The macroalgae sector must be included and treated as part of the agricultural sector—with support for research, education, training, and investments in infrastructure. The social and environmental

benefits of macroalgae activities must be compensated and global knowledge sharing and collaboration need to be enhanced. The *International Bioeconomy & Macroalgae Center* established in 2024 at the University of California, Berkeley is a nexus of global collaboration in developing the expanding macroalgae sector.

With the right commitment, the macroalgae sector could grow far beyond its current $10–17 billion value, potentially becoming a $100 billion or even a trillion-dollar industry within a few decades. Doing so will require a long-term vision, cross-sectoral collaboration, and a willingness to invest in both science and infrastructure. The time to act is now—so that macroalgae may evolve from a niche product into a cornerstone of the sustainable global economy.

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Chapter 21
Bioenergy for Inclusive and Sustainable Economic Growth

David Wells Roland-Holst and David Zilberman

21.1 Introduction

Alternative approaches to managing biomass energy offer significant potential for mitigating emissions, achieving energy independence, and fostering sustainable employment growth in economically disadvantaged regions. Globally, biomass energy remains extensive, but it is generally very inefficient and hazardous, both in terms of safety and air quality. In more advanced economies, it is more likely to be treated as a waste product with positive net costs for disposal, including methane and other GHG emissions, air and water pollution, and toxic by-products.

California faces major environmental and economic challenges. Over the last few years, the state has experienced catastrophic damage from wildfires linked to climate change. Meanwhile, there is a perennial need for new income sources to improve livelihoods in rural California. Many innovative strategies have been introduced to address climate risk, including solar and wind power. However, these alone may be insufficient to offset significant climate change and the escalation of the damages that we are already witnessing.

21.2 Bioenergy Background

Biomass energy conversion refers to the processes through which various forms of organic matter, including agricultural residues, forestry by-products, and municipal solid waste, are converted into usable energy forms such as electricity, heat, and biofuels. As society seeks to reduce greenhouse gas emissions and transition to

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renewable energy sources, biomass has emerged as a viable alternative to fossil fuels.

Biomass energy comes from organic materials, including wood, agricultural crops, and other biogenic waste products. It is considered renewable because its fuels are derived from biological processes that can continue indefinitely, provided that its feedstocks are sourced sustainably.

21.2.1 Innovation Potential in Biomass Energy

To date, biomass conversion technologies have been relatively inefficient and emission-intensive. Recent innovations in anaerobic pyrolysis systems are rapidly evolving, with the potential for waste biomass to replace natural gas and other fossil fuels in electricity production. This transition from natural gas to biofuels will be gradual. It can benefit from improvements in biomass conversion technology and pricing that recognize the negative externalities of fossil fuels and the important co-benefits of utilizing residue feedstocks (e.g., reduction of fire risk). Bioenergy innovation efforts are presently concentrated in three general areas.

21.2.1.1 Thermochemical Conversion

Thermochemical bioenergy conversion involves applying heat and/or chemical agents to denature or "crack" biomass materials, thereby separating their pure carbon molecule components into gaseous (syngas), liquid (biodiesel, bio-gasoline, etc.), and solid (biochar) forms. The mitigation benefits of these are twofold: biofuel can displace fossil fuel, and biochar can sequester carbon. Three types of thermochemical conversion are currently most popular:

- **Gasification:** Biomass is converted into syngas (a mixture of hydrogen, carbon monoxide, and carbon dioxide) through high-temperature processing in an oxygen-starved environment. This gas can be used for electricity generation or as a feedstock for producing chemicals and fuels.
- **Combustion**: The direct burning of biomass to produce heat is the most straightforward conversion method. Biomass fuels can be burned in dedicated power plants or co-firing setups with coal.
- **Pyrolysis**: Biomass is heated in the absence of oxygen, leading to the formation of bio-oil, biochar, and syngas. Bio-oil can be further refined into transportation fuels.

21.2.1.2 Biochemical Conversion

This category of bioenergy conversion is sometimes referred to as "passive." It uses microbial agents to convert biomass into biofuel and a variety of residuals. These have been quite popular conversion pathways for more homogeneous feedstocks with high water content, such as animal waste. The main biochemical pathways for biochemical conversion are two:

- **Anaerobic Digestion**: Organic matter is broken down by microorganisms in an oxygen-free environment to produce biogas (mainly methane) and digestate. Biogas can be utilized for heating, electricity generation, or as a vehicle fuel.
- **Fermentation**: Sugars derived from biomass feedstocks (typically starches or cellulose) are converted into ethanol or other biofuels through microbial processes.

21.2.1.3 Other Technologies

A few other biomass conversion technologies are more specialized, but are less likely candidates for large-scale energy development, including the following:

- **Transesterification**: This process converts oils and fats (usually from vegetable oil or animal fat) into biodiesel through chemical reactions with alcohol.
- **Hydrothermal Liquefaction**: Biomass is converted into biocrude oil and other products in high-pressure and high-temperature conditions, enhancing the energy density of biomass.

21.2.2 Adoption Challenges for Bioenergy

Like many innovation processes that address deeply embedded socioeconomic needs and technology norms, new bioenergy faces a number of fundamental challenges to its wider adoption and diffusion. A few of the leading issues are summarized here.

- **Sustainability Concerns:** Harvesting biomass without sustainability considerations can lead to deforestation, loss of biodiversity, and soil degradation. Ensuring that biomass is sourced sustainably is crucial for the long-term viability of biomass energy.
- **Competing Land Use:** The demand for biomass feedstocks can lead to competition with food production. Critical consideration must be given to land use and management practices to avoid negative impacts on food security. The so-called "food-fuel" tradeoff will continue to present a serious challenge to the use of comestible feedstocks. Still, much research in this area is dedicated to expanding agrifood productivity to compensate for such tradeoffs.

- **Technology Barriers:** Many biomass conversion technologies are still in the early stages of commercial deployment, and significant technological advancements are needed to enhance efficiency and cost-effectiveness. The high cost of advanced biofuels and the limited availability of feedstocks are substantial barriers to widespread adoption.
- **Public Perception and Acceptance:** Misunderstandings about biomass energy, including concerns about air quality and emissions from combustion, have hindered public support for bioenergy conversion. Effective communication about the lifecycle benefits and sustainability of biomass energy is crucial.
- **Logistical Challenges:** The collection, transportation, and pre-processing of biomass feedstocks can be logistically complex and costly and, if carbon-fueled transport is involved, can offset mitigation potential. Developing efficient and sustainable supply chain management strategies to minimize costs and ensure consistent feedstock quality is essential.

21.2.3 Biomass Energy Production in the USA

The number of dedicated biomass power plants in the USA exceeded 250 by the beginning of this decade, generating approximately 14 terawatt-hours (TWh) of electricity (EIA, 2021). Focusing on biofuels within the renewable energy portfolio, the USA leads the world in the production of ethanol, primarily from corn starch, with over 16 billion gallons produced annually (USDOE, 2021). The primary pathway for this green energy is blending with gasoline.

The economic benefits of bioenergy are growing, already substantial, and diverse. As emphasized in the California discussion below, bioenergy development has the potential to create new long-term employment in rural areas through feedstock production, processing, and facility operations. According to the Biomass Power Association (2021), this emergent industry already supports approximately 100,000 jobs in the USA. Moreover, by harnessing domestic biomass resources in this way, the USA can reduce its dependency on imported fuels and enhance energy security at the local, state, and national levels.

Across the USA, a variety of policies have been implemented to promote biomass energy, including the following:

- **Renewable Fuel Standard (RFS)**. The RFS, established under the Energy Policy Act of 2005, mandates the blending of biofuels into the transportation fuel supply. The program has significantly bolstered the production of corn-based ethanol and advanced biofuels from non-starch feedstocks.
- **Investment Tax Credits (ITC)**. These tax credits incentivize capital investment in biomass facilities by reducing the upfront costs of development, making biomass more competitive with fossil fuels.

- **State-Level Initiatives**. Various states have adopted Renewable Portfolio Standards (RPS), which require utilities to procure a certain percentage of their energy from renewable sources, including biomass.

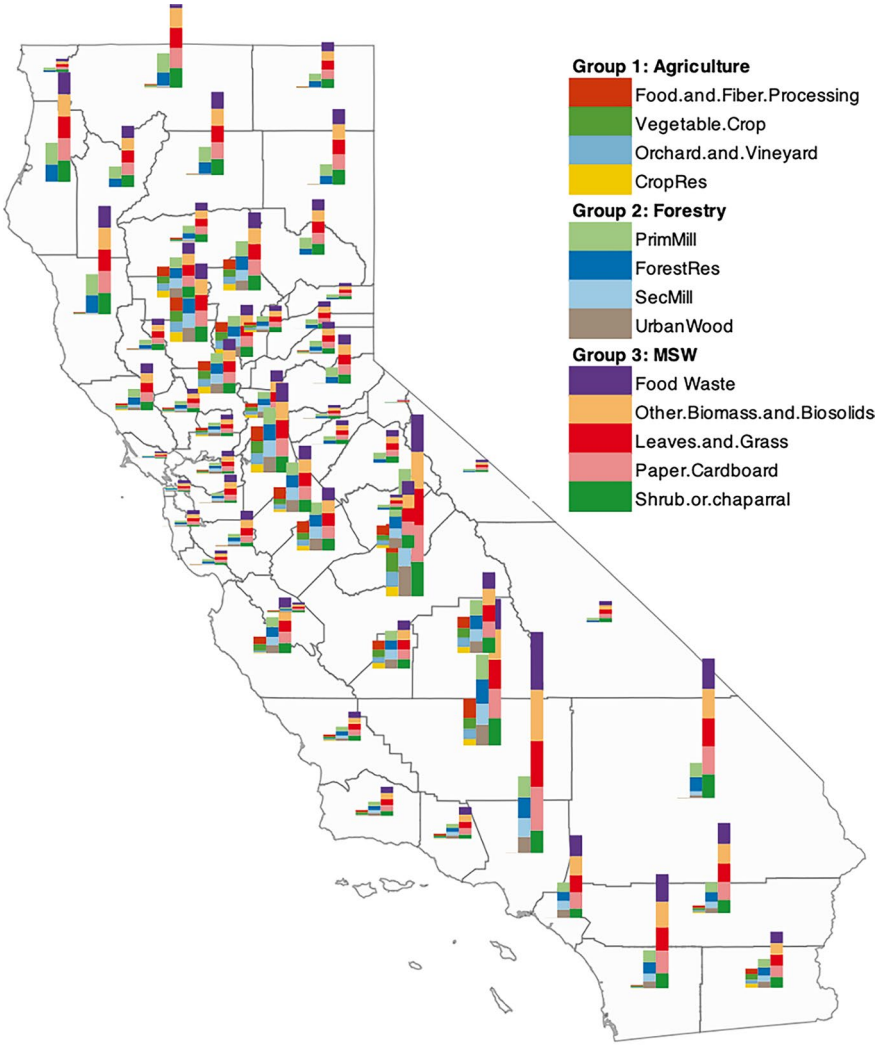
21.2.4 California's Bioenergy Landscape

In California, bioenergy provides immediate opportunities to address salient climate challenges, including the risk of catastrophic wildfires, while reducing rural–urban economic disparities. In the larger context of the bioeconomy, bioenergy conversion combines natural, human, and technical resources to expand the range of products from agriculture beyond food and fiber, including clean fuels, fine chemicals, carbon sequestration, plastics, and a variety of resource services, including improved air/water quality, carbon sequestration, etc. The modern bioeconomy emphasizes circularity—reducing, reusing, and recycling residues from production as inputs to new economic activities. Residues from agricultural and natural resource processing, including forestry, crop, and food residues, as well as animal waste, pose public health and safety risks. Redirecting them to higher value refined products can increase local employment, value-added, and income while reducing social costs.

The paper discusses pathways for reusing biomass, including organic residues from forests, landscapes, agriculture, and municipalities, which can be processed into biofuels or biochar. We highlight that this biomass is a goldmine of renewable resources, which, if utilized, could be win-win-win-win-win in terms of (1) reducing huge waste volumes, (2) reducing fire risk, (3) lessening California's dependence on fossil energy sources (mostly imported from out of state), (4) reducing greenhouse gas emissions, (5) and providing new sources of employment and income for rural and low-income communities. The development of this new resource can be accelerated by prioritizing California resources in the State's Low Carbon Fuel Standard (LCFS) over other providers of low-carbon fuels from other states.

California's rural and urban economies produce vast amounts of biomass residues, with an annual flow of over 50 million bone dry tons per year (MBDT/yr), as shown in Fig. 21.1. Approximately 24 MBDT/yr. of this waste consists of forest products and landscape trimmings, and the supply is growing rapidly due to efforts to reduce forest fire risk. Agriculture and municipal solid waste (MSW) operations contribute approximately equal amounts (10.4 and 12.3 MBDT/yr., respectively), and landfill waste currently accounts for about 7.1 MBDT/yr. Altogether, this amounts to 54 MBDT per year.

Waste streams in California consist of forestry, agriculture, gaseous, and municipal wastes. Forest residue includes waste from forest management and lumber production. Agricultural biomass includes residues from crops, orchards, vineyards, and gaseous animal waste. Municipal solid waste comes mostly from cities and the urban sector.



Category	2025	2045
Forest	24	24
Agriculture	10	13
MSW	19	19
Total	54	56

Forest and Agriculture in Bone Dry Ton equivalents.
MSW Includes landfill and digester gas
Source: Baket et al: 2020

Fig. 21.1 Biomass waste streams in California. (metric tons by type and county)

This accumulating biomass poses a threat to combustion, as well as to air, water, and soil contamination. California's biomass challenge is to reduce the volume of this waste and utilize the energy services of its carbon content before it returns to the atmosphere via combustion or decay.

21.2.4.1 Converting Biomass to Valuable Products

Several bioenergy innovations can convert these environmental liabilities into assets. The annual biomass flow represents about 100 million metric tons (MMT) of carbon dioxide equivalent (CO_2e) emissions. These capabilities are based on a new generation of thermal, anaerobic bioenergy conversion technologies that can capture over 90% of feedstock carbon. When biomass is heated without oxygen through a process called "gasification," organic carbon is converted to three generic outputs: gas (syngas), liquid (bio-oil), and solid (biochar). Bio-oil is a viscous mix of oxygenated organic compounds with 50%–70% of the energy potential of petroleum. This liquid fuel can be used directly as heating oil or refined to more advanced biofuels. Biogas, also known as syngas, is utilized in power generation for steam, gas engines, or turbines. Biochar is a stable, nearly pure carbon solid. Adding biochar to soils can enhance their water retention and contribute to improved soil health and productivity. Biochar made at the high temperatures of modern gasification can sequester carbon for hundreds of years. More than 15 firms in California produce biochar, biogas, and other products through gasification, with some dating back more than 10 years. They are mostly small, but technological improvements allow for the emergence of larger and more diverse firms.

The output of gasification depends on feedstock composition, reaction type, time, temperature, and pressure. Slow gasification (hours to days) requires a relatively low temperature (550–750 °F) and results mostly in charcoal, whereas fast gasification (which may take seconds) occurs at very high temperatures (750–2000 °F) and may produce mostly liquid fuels (biodiesel, bio-gasoline, and bio-J4) and syngas. Innovations continue to reduce costs and increase input-use efficiency, as well as promote downward scalability.

Biomass gasification can yield 90% feedstock carbon conversion to biofuels. Based on the latent carbon in existing waste streams across the state, this represents the mitigation potential of about half of California's entire 2050 scoping plan to implement the Global Warming Solutions Act (Assembly Bill 32). The energy needed to sustain gasification typically falls between 3%–15% of the total energy contained in the biomass feedstock, with an average of 8%. Conversion of biomass to biofuels also entails emissions from biomass removal, collection, and transportation. Gasification can utilize renewable energy sources (such as solar, wind, or biofuel), further enhancing the greenhouse gas (GHG) efficiency of the process. Considering its complete life cycle, gasification (conversion, collection, and transportation) can yield between 40%–70% of the carbon content of the biomass, depending on the feedstock and the processing. This is a combination of the efficiency of the conversion, subtracting out the energy used in its generation.

The primary contribution of bioenergy conversion is reducing California's reliance on non-renewable sources, but, depending on the feedstock, there are also important co-benefits, including reductions in wildfire and local pollution risks. Transportation consumes 42% of California's energy. Household heating and electric power consume about 35%, and the final 23% goes to industry. Bioenergy, which encompasses syngas and biofuels, has the potential to replace a substantial portion of the natural gas and liquid fuels used for electricity generation and transportation. The primary challenge is to reduce production costs, which can be achieved through continuous research, economies of scale, and learning by doing. Lower costs will accelerate the adoption of bioenergy. Adoption will also increase if bioenergy is compensated for its low GHG emissions (as part of the Low Carbon Fuel Standard) and for the reduction of fire risk that the elimination of wastes entails.

21.2.4.2 Biofuel for Electric Power in California

Despite its energy and mitigation potential, biomass has been a chronic underachiever in the state's electric power portfolio. Half of California's electricity supply comes from natural gas, about 30% from renewables, and only 3% from biomass. Traditional biomass conversion technologies have been inefficient and produced abundant emissions. Recent innovations in anaerobic gasification systems are rapidly emerging to expand green electricity production. Some of the liquid and gaseous biofuel from the gasification of waste biomass can displace natural gas. The transition from natural gas to biofuels will be gradual and can benefit from improvements in biomass conversion technology and pricing that recognize the social benefit of using residue feedstocks to reduce GHG emissions and fire risk.

Despite its potential, biomass remains an underutilized resource in the US renewable energy landscape, accounting for approximately 5% of total US energy consumption (EIA, 2021). As Fig. 21.1 indicates, half of California's electricity supply comes from natural gas, about 30% from renewables, but only 3% from biomass (Fig. 21.2).

Biomass can make essential contributions to reducing fossil fuel dependence, particularly in ground and air transportation. The Department of Energy (DOE) has studied the estimated biomass potential within the United States, with reference to a goal of replacing up to 30% of petroleum consumption with biofuel (see Fig. 21.3). Pyrolysis-based biofuel can play an important role in replacing fossil fuels, especially for aviation and marine transportation.

21.2.4.3 Biochar Production

In modern pyrolysis, about 14% of the biomass is converted to biochar. Biochar contributes to soil health through its role in water retention, microbial activity, and enhanced soil health and agricultural productivity. It has also a proven capacity to store carbon from biomass that would otherwise be burnt or decomposed into methane and other greenhouse gas emissions. The value of biochar will be further

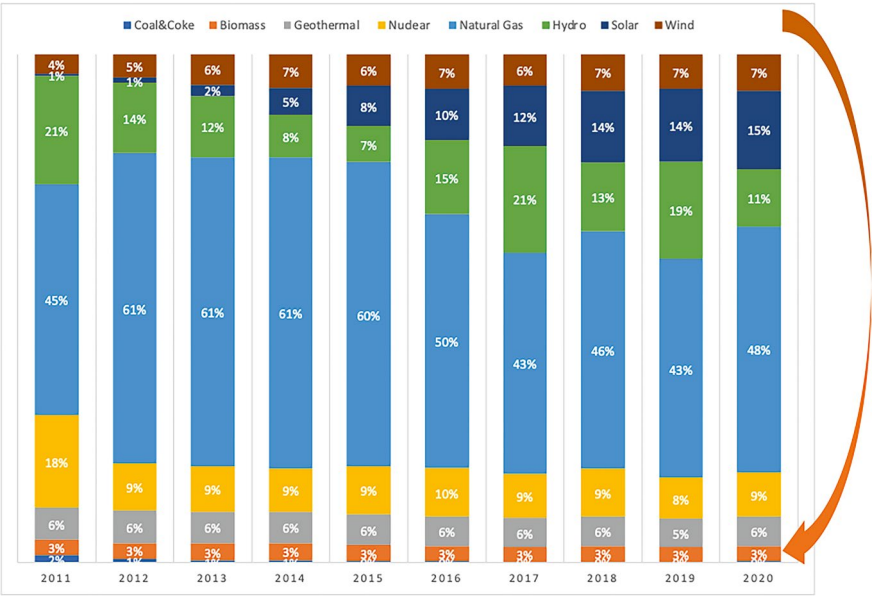


Fig. 21.2 California's electric power mix

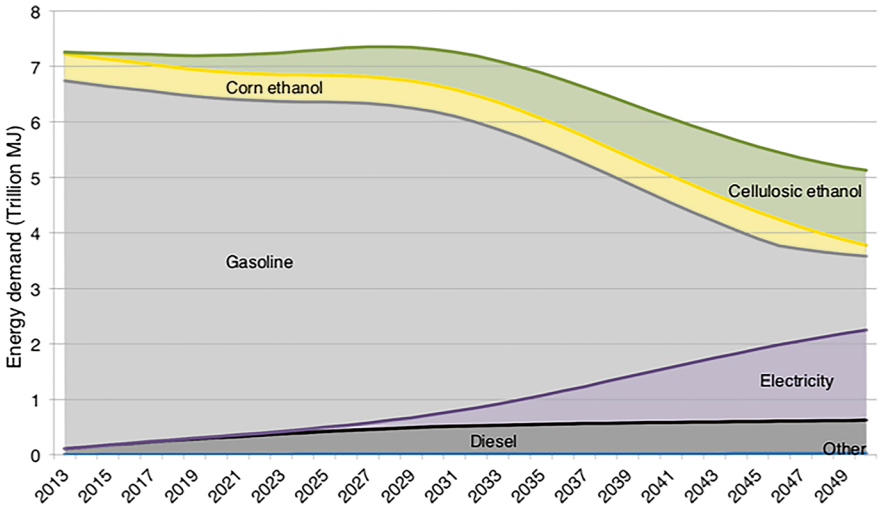


Fig. 21.3 Projected total passenger vehicle fleet fuel demand (trillion MJ/year). Source: Scown et al.: 2012

enhanced when the California state agencies, including the California Department of Food and Agriculture (CDFA) and the California Air Resources Board (CARB), recognize biochar's full mitigation potential. It can also be converted into a variety of more valuable activated carbon products, essential for water, food, and pharmaceutical filtration and processing activities.

21.2.5 Economic and Social Impacts and Policy Considerations

Pyrolysis-based technologies have made major progress in terms of cost-effectiveness and conversion efficiency. While they continue to face challenges from high capital costs, feedstock management, and fuel compatibility, their advantages are increasingly apparent, particularly in light of escalating wildfire risk, rising landfill costs, and the emergence of credits for mitigation and ecosystem services. In the current policy environment, recent designs of pyrolysis-based technologies using forest and other biomass residues are profitable and have attracted substantial investor interest.[1]

21.2.5.1 Benefits to Rural Communities

Another distinguishing feature of new bioenergy conversion technologies is scale. These systems can be built to utilize the biomass produced by small rural communities, generating biofuel for electricity and transportation. These biofuel facilities will generate local carbon energy and sequestration, improve local employment and wealth, while reducing pollution, enhancing air, water, and soil quality, and promoting energy equity. Of course, not every community would have sufficient biomass feedstocks to be energy-independent. The regions of California with the highest density of biomass feedstock are rural areas, including those with heavy forest cover and intensive agriculture. As indicated in Fig. 21.3, these areas are more likely to be economically disadvantaged and have higher per capita energy costs (mainly because of lower winter temperatures and more remote logistics).

This local bioenergy opportunity is still emerging but already enjoys public support. With its Forest Biomass to Carbon-Negative Biofuels Pilot Program, the California Department of Conservation, in close coordination with the California Energy Commission and the California Air Resources Board, dedicated $50 to promoting biomass energy conversion. In 2023 alone, they awarded $500,000 to eight pyrolysis projects in Sierra Nevada communities.[2] Six different technologies were deployed in this grant-making, but these represent only a fraction of the innovation in this new energy arena (Fig. 21.4).[3]

Despite other economic disadvantages, lower-income rural areas of the state have a distinct comparative advantage in terms of bioenergy potential. Comparing

[1] For examples of patented technologies that are already being used in rural areas for carbon-negative local biomass conversion, see e.g. https://arbor.co/, https://www.biogas-energy.com/site/index.html, https://sierrainstitute.us/program/biomass/, https://www.yosemiteclean.com/

[2] https://www.conservation.ca.gov/index/Pages/News/State-Invests-3-Million-Convert-Forest-Waste-into-Carbon-Negative-Fuel.aspx

[3] For overviews of this rapidly emerging technology, see e.g., Pereira et al., 2012 and Molino et al., 2016

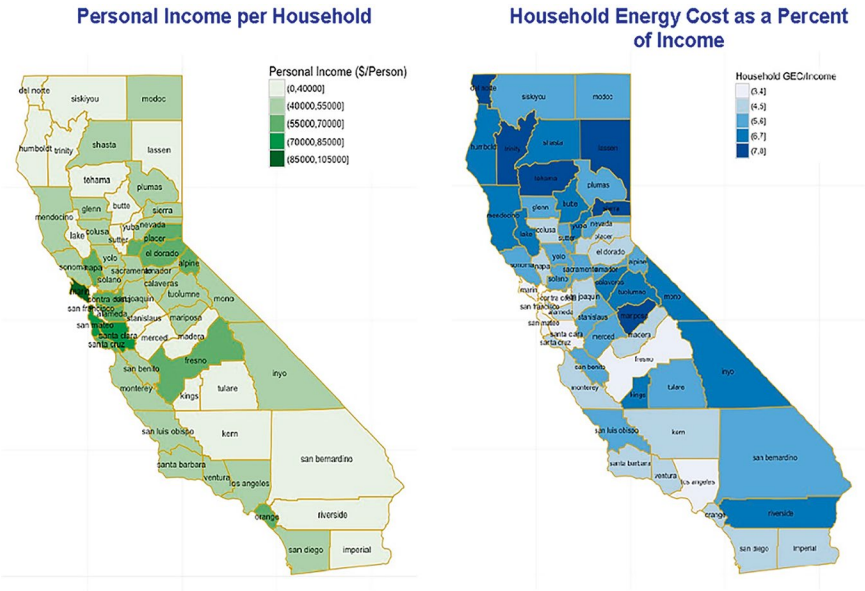


Fig. 21.4 Energy economics of Sierra communities

biomass resources and average income per capita across the state's 58 counties, Fig. 21.5 suggests that bioenergy trade across the state could benefit disadvantaged counties.

21.2.5.2 Incorporating Local and Global Externalities in Regulatory Frameworks

The development of a biofuel sector relying on waste biomass in California will benefit from policy changes. One example is the modification of the Low Carbon Fuel Standard (LCFS). The Low Carbon Fuel Standard (LCFS) is a hallmark of CARB's commitment to reduce climate risk arising from mobile fossil fuel emissions. Despite the global GHG reductions achieved by this program; however, its contribution to California's own environmental, public health, safety, and economic challenges has been unnecessarily limited (Fig. 21.6).

This major policy considers only a reduction in greenhouse gas emissions from transportation without recognizing the local benefits, such as mitigating local air pollution or reducing fire risk. As a result, people from all over the world can produce bioenergy and be rewarded by California taxpayers. Indeed, only 30% of the projects certified for LCFS emission credits are inside the state. Among over 700 approved LCFS pathways are swine production in MO, subsidized corn processing in the Dakotas, and cooking oil recycling in Singapore. By giving more attention to

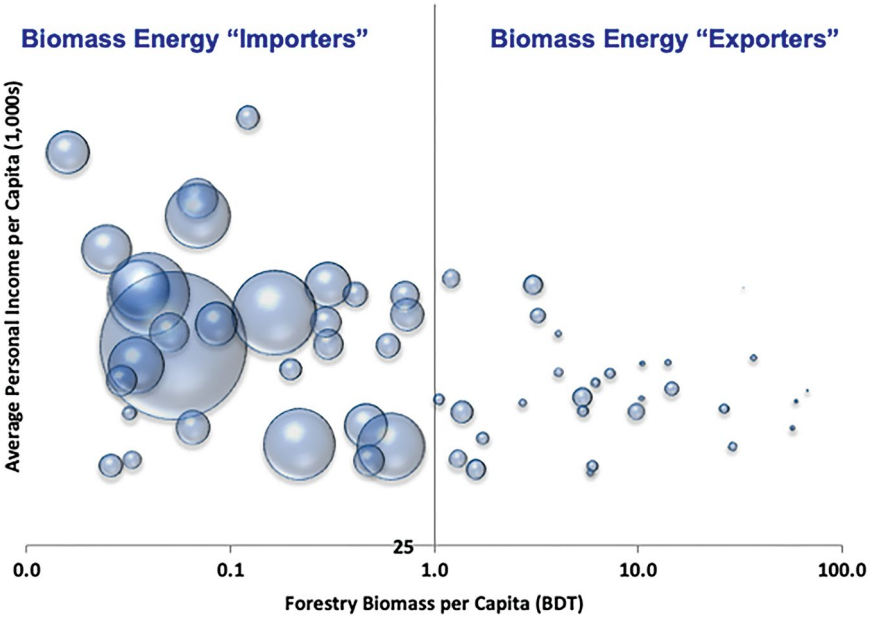


Fig. 21.5 Biomass and income per capita by county. Source: US Census and Baker et al. (2020). Bubble diameter is proportional to population

local needs, California's regulatory framework could prioritize biofuel pathways that directly serve a variety of state goals, in addition to greenhouse gas (GHG) reduction—a notable example is woody biomass to reduce fire risk. Increasing the likelihood that California renewables are eligible to participate in the LCFS may require modifying the LCFS to include state co-benefits in its formula. In particular, the reduction of expected losses from fire risk due to the conversion of woody biomass to biofuel can be added to the value of these biofuels in the LCFS formulas.

21.3 Conclusions

The future of biomass energy conversion in the USA looks challenging but very promising. As supporting technologies continue to advance, particularly in areas like gasification and anaerobic digestion, biomass conversion may become more efficient and economically viable. To achieve this, future investments in research and development will be critical in expanding the role of biomass in the renewable energy landscape.

In California, the conversion of waste biomass can simultaneously help address fire risk, local air pollution, greenhouse gas emissions, and the burgeoning organic waste volumes around the state. At the same time, it promises a new source of

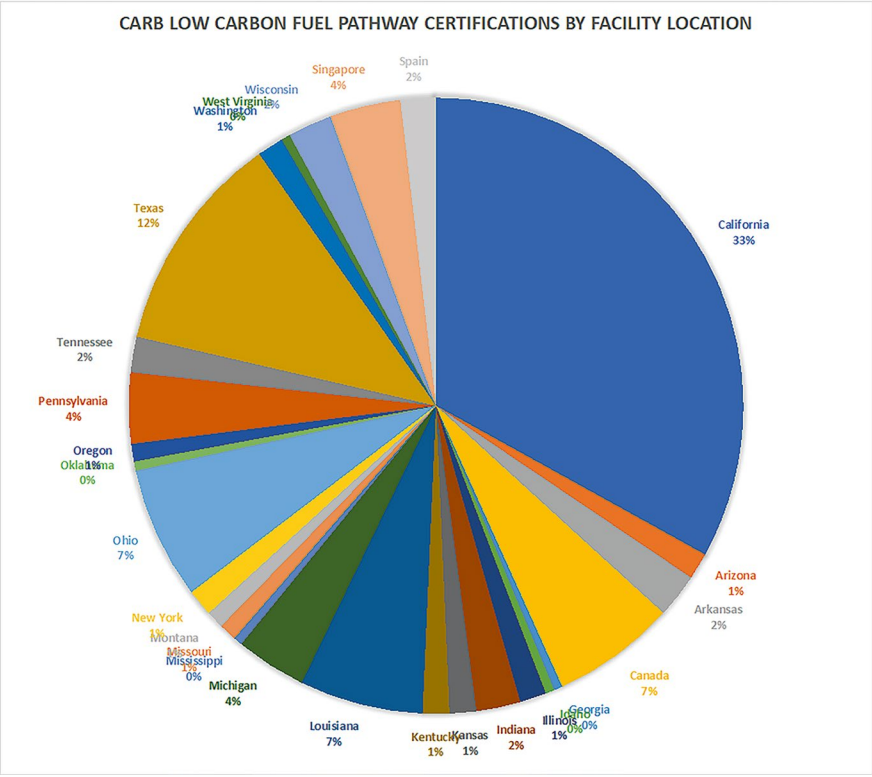


Fig. 21.6 Outsourcing toxic emission reduction and green jobs?

income to California, especially in rural communities. Meanwhile, regulatory frameworks must evolve to support the development of biomass innovation, market growth, and sustainable practices.

Technology development must also be supported by public and private efforts to improve awareness and support constructive policy dialogue. Engaging stakeholders, including farmers, industry representatives, policymakers, and the general public, will be crucial in addressing concerns and promoting biomass production and utilization. Greater recognition of local benefits, including new employment opportunities, energy independence, and improved air and water quality, will support a robust bioeconomy in California. That result, another knowledge-intensive California success story, can be a model for the rest of the world.

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Part III
Circular Bioeconomy Practices in Latin America and Around the World

Chapter 22
China's Bioeconomy Transition: A Policy Framework

Mengshuai Zhu, Kutay Cingiz, and Justus Wesseler

22.1 Introduction

The rapid advancement of life sciences and biotechnology has become a powerful engine driving the growth of bioindustries and the evolution of the bioeconomy. As an innovative economic paradigm, the bioeconomy harnesses biological resources and biotechnology to develop sustainable solutions addressing critical global challenges such as food scarcity, energy crises, and environmental pollution (Kardung et al., 2021; Wesseler & Zhu, 2024). By integrating biological systems with modern technology, the bioeconomy offers comprehensive approaches to enhance food production systems, develop renewable energy alternatives, engineer novel bio-based materials, and implement effective environmental conservation strategies (Wesseler & von Braun, 2017; Zilberman et al., 2018). This global shift toward biological solutions represents a fundamental reimagining of economic systems, moving from fossil fuel dependence to circular, regenerative models that align with the sustainable development goals of the United Nations (El-Chichakli et al., 2016; Ronzon & Sanjuán, 2020).

China is strategically advancing its bioeconomy by leveraging unique advantages that ensure long-term, high-quality development. The nation's massive population of 1.4 billion people, including a rapidly expanding middle class exceeding 400 million consumers (Huld & Interesse, 2023), provides an unparalleled domestic

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market for bio-based products and services. Furthermore, the aging society with life expectancy surpassing 78 years drives substantial demand for advanced biopharmaceuticals and healthcare services. These fundamental market forces, combined with China's comprehensive industrial ecosystem and strong policy support, position the country to lead the global bioeconomy transformation.

China is rapidly emerging as a global leader in the bioeconomy. According to Zhu et al. (2025), using a hypothetical extraction method with OECD input–output tables, China's bioeconomy has generated the highest value-added since 2011, reaching over 989 billion dollars (1995 = 100)—significantly surpassing the USA at 632 billion dollars. The Chinese government has implemented a comprehensive policy framework to accelerate bioeconomy growth (Wang et al., 2018a). Key initiatives include a series of Five-Year Plans, which identify biotechnology as a national priority sector, and dedicated bioeconomy plans, such as the *14th Five-Year Plan for Bioeconomy Development (2021–2025)*, which strategically prioritizes four key sectors: biomedicine, bio-agriculture, biomass substitution, and biosecurity (NDRC, 2022). While challenges such as intellectual property protection and international competition remain, China's unique combination of market scale, policy support, and technological capability positions the country for continued expansion in this strategically important sector.

This study conducts a comprehensive analysis of China's bioeconomy policies, examines the current development status of core sectors, and provides forward-looking insights into both opportunities and challenges for future advancement.

22.2 The Evolution of Chinese Bioeconomy Policies

The biotechnology journey in China began in 1965 when scientists made history by successfully synthesizing bovine insulin, becoming the first nation to artificially produce a biologically active protein and demonstrating the feasibility of laboratory biomolecule synthesis (Wang et al., 2018a). The 1970s saw another landmark achievement with Youyou Tu's discovery of artemisinin from sweet wormwood, an antimalarial compound that revolutionized global malaria treatment and earned her China's first Nobel Prize in Physiology or Medicine in 2015 (J. Wang et al., 2019).

China's strategic focus on biotechnology began taking institutional shape in the 1980s when the State Science and Technology Commission made genetic engineering a priority in the sixth Five-Year Plan (1981–1985). This marked the first official inclusion of genetic engineering in national scientific programs, with targeted funding allocated for critical projects including interferon production, hepatitis B vaccine development, and plant genetic improvement (Wang et al., 2018a). The government progressively expanded its commitment during the 7th (1986–1990) and 8th (1991–1995) Five-Year Plans, in which genetic engineering was broadened into comprehensive biotechnology development programs. Also, the first comprehensive *National Biotechnology Development Policy Outline* was launched in 1988. This outline delineated research priorities, laid out the development plan, and

prescribed measures to attain specified targets or goals (Huang & Wang, 2002). This period saw increased Research and Development (R&D) funding and the establishment of specialized research institutes to advance both therapeutic applications (like vaccine development) and agricultural innovations. The systematic support across three consecutive Five-Year Plans enabled China to achieve early breakthroughs, including the world's first commercialized hepatitis B vaccine using recombinant DNA technology in the 1990s. China further demonstrated its bioscience capabilities through its participation in the Human Genome Project (1999–2003), where it contributed 1% of genome sequencing, significantly advancing the country's genomics and precision medicine research (Li et al., 2006; Wang et al., 2018b).

China's bioindustry entered a phase of accelerated, strategic development in 2006 when it was elevated to a top national economic priority. In 2006, *the National Medium- and Long-Term Science and Technology Development Program* was issued, with biotechnology as one of eight cutting-edge technologies, and protein research, and development & reproduction as two of the four major scientific research programs. Afterward, the National Science and Technology Major Project (NSTMP) was initiated in 2006 with 16 major projects, of which three are related to biotechnology: the Major Breeding Projects of GMOs Varieties (GMMP), the Major New Drug Creation Program, and the Major Project on Prevention and Control of Major Infectious Diseases such as AIDS and Viral Hepatitis.

In 2007, the *11th Five-Year Plan for the development of bioindustry* was issued, to promote biomedicine, bio-agriculture, bioenergy, biomanufacturing, and bio-environmental protection. The plan sets the goal of achieving a bioindustry value-added of 500 billion RMB, accounting for 2% of GDP, by 2010, and 2 trillion RMB, accounting for 4% of GDP, by 2020 (NDRC, 2007). In 2010, the State Council officially classified the bioindustry as one of China's seven Strategic Emerging Industries. The government subsequently defined seven core sectors of bioindustry in 2012: biomedicine, biomedical engineering, bio-agriculture, bioenergy, bio-based manufacturing, bio-environmental protection, and biotech service. This comprehensive framework stimulated remarkable growth, with the bioindustry achieving a 22.9% average annual expansion rate and surpassing 2 trillion RMB in total output value by 2011. The consistent 20% + growth maintained from 2013–2015 demonstrated the sector's increasing contribution to China's economic transformation.

The *13th Five-Year Plan for the development of bioindustry* revised the targets, setting a goal of achieving a bioindustry value between 8–10 trillion RMB by 2020. The breakdown of this target includes 4.5 trillion RMB for biomedicine, 0.6 trillion RMB for biomedical engineering, 1 trillion RMB for bio-agriculture, 1 trillion RMB for biomanufacturing, and 0.2 trillion RMB for bio-environmental protection (NDRC, 2016). This period marked the transition from basic research to more commercialization, with particular emphasis on securing independent intellectual property rights—a crucial step in reducing foreign technology dependence.

In 2022, the first national bioeconomy plan of China, the *14th Five-Year Plan for bioeconomy Development*, was issued. While the plan did not provide a precise definition of bioeconomy, it described it as being.

> driven by the development and progress of life sciences and biotechnology, based on the protection, development, and utilization of biological resources, and characterized by the extensive and in-depth integration of the pharmaceutical, health, agricultural, forestry, energy, environmental protection, materials, and other industries.

The plan also emphasized that the bioeconomy is outlining a beautiful blueprint for the future development of human society. Although no specific numerical targets were set, the plan prioritizes the development of biomedicine, bio-agriculture, biomass substitution, and biosafety (NDRC, 2022; Zhang et al., 2022).

Some provinces also issued specialized plans for the bioeconomy. In 2019, the *Zhejiang Bio-economy Development Action Plan (2019–2022)* set the objectives of accelerating the bioeconomy development of biomedicine, bio-digital service industry, bio-agriculture, bio-based materials, bio-environmental protection, bioenergy, and marine life. In 2022, the *Heilongjiang 14th Five-Year Plan for the Development of the Bioeconomy* focuses on developing biomedicine, biomanufacturing, bio-agriculture, bio-environmental protection, and biomedical engineering.

With the continual support for biotechnology, China's biotechnology innovation capacity has seen a dramatic increase. Figure 22.1 illustrates the total number and proportion of biotechnology patents filed by applicants from China. Both patent publications and grants saw a dramatic increase between 2000 and 2023. The number of publications rose from 428 in 2000 to 36,129, an increase of more than 80 times. Similarly, the number of granted patents grew from 122 to 18,725 over the same period, marking an almost 153-fold rise. Currently, China's biotechnology patent publications account for 42.84% of the global total, while the granted patents make up 50.68% of the world total. This highlights China's significant and growing presence in global biotechnology innovation and intellectual property.

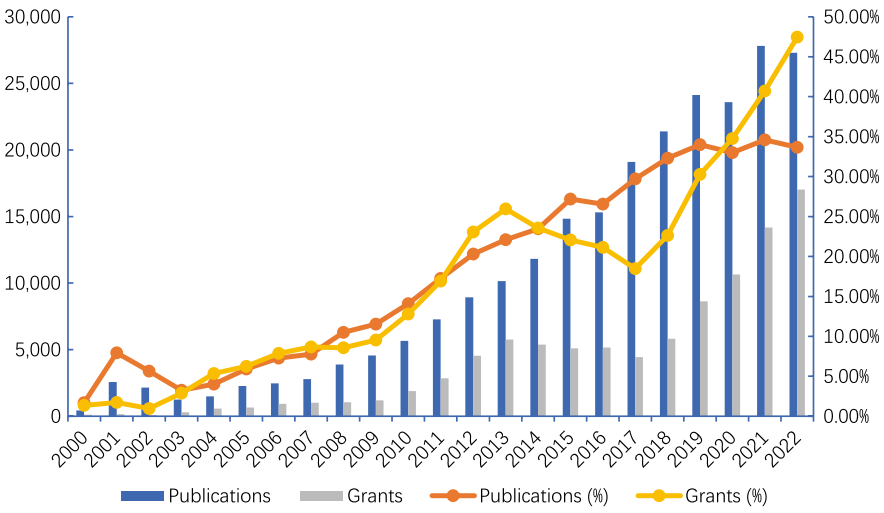

Fig. 22.1 Total number and proportion of biotechnology patent filed by applicants from China (Data source: WIPO)

22.3 Key Sectors

The China Bioeconomy Development Report 2024 outlines seven core industries—biomedicine, bio-agriculture, biomanufacturing, biological environmental protection, bioenergy, bioinformatics, and biomedical engineering—as the pillars of China's growing bioeconomy (NDRC, 2024). We demonstrate the characteristics and future directions of these bio-sectors.

22.3.1 Biomedicine

Biomedicine, using biotechnology for treating diseases and improving healthcare, is a strategic emerging industry of China's bioeconomy and is seeing a significant increase. The biopharmaceuticals market size in 2020 was 345.7 billion RMB and is projected to account for 811.6 billion RMB by 2025. The market value of publicly listed bio-pharma innovation companies from China surged from $3 billion in 2016 to over $380 billion by July 2021 across the Nasdaq, Hong Kong Stock Exchange (HKEX), and Shanghai Stock Exchange Science and Technology Innovation Board (STAR). This growth reflects significant advancements in the sector, driven by increased R&D investments, a strong pipeline of innovative drugs, and supportive policies (Han et al., 2021). The China Biomedical Industry Barometer (CBIB), a national-level index for the biomedical industry in China, revealed a nearly 55% increase in 2022 compared to 2019, showing generally rising investment, higher corporate profits, more job opportunities, and a surge in innovative products within the sector (NDRC, 2024).

China is actively expanding its biomedicine industry, with multiple provinces setting ambitious targets to establish large-scale industrial clusters. Heilongjiang is building a 100 billion-level (RMB) Harbin Bio-Pharmaceutical Industrial Park and a 10 billion-level (RMB) Harbin Veterinary Research Institute International Bio-Valley. Tianjin is developing specialized bio-pharma parks with independent medical logistics centers. Shandong aims to grow Jinan's bio-pharma industrial chain to 300 billion RMB by 2025. Henan targets a 400 billion RMB industry scale in the same period. Shanghai is focusing on biomedicine manufacturing, aiming for 240 billion RMB in production value. Zhejiang expects to reach 450 billion RMB in bio-pharma output by 2024. Guangdong has the most ambitious goal, targeting 1 trillion RMB in bio-pharma revenue by 2025. Collectively, these initiatives at the provincial level demonstrate China's strategic push to dominate the global biopharmaceutical market.

In line with the new trend of shifting from a "treatment-centered" to a "health-centered" approach, China's biomedicine will focus on early disease prevention, improved diagnostics, and enhanced clinical treatments. It promotes the integration of genetic testing and biotechnology for early screening of major diseases such as cancer and cardiovascular conditions, alongside accelerating the development of

advanced vaccines. Diagnostic capabilities are to be improved by combining biotechnology with precision machinery and new materials, aiming for smarter, smaller, faster, and more precise diagnostic tools and medical imaging. It also emphasizes advancing clinical treatments through innovations like microfluidic chips, gene therapy, and biopharmaceuticals, while expanding the use of robotic surgery and digital therapies. Furthermore, it advocates for integrating Chinese traditional medicine with modern biotech and ensuring the standardized use of antimicrobial drugs.

22.3.2 Bio-Agriculture

China's agricultural development is fundamentally driven by the urgent need to ensure food security while addressing the challenges of limited arable land (accounting for just 7% of the world's total for about 19% of the world population), a huge population, and frequent natural disasters. Bio-agriculture, which integrates advanced biotechnology with traditional agricultural practices, is increasingly recognized as a sustainable and effective solution to many of the challenges. The integration of biotechnology with various sectors of agriculture has given rise to innovative and sustainable approaches, leading to the development of key industries such as bio-breeding, biofertilizers, and biopesticides.

Bio-breeding involves the use of biotechnological tools such as genome editing (e.g., CRISPR-Cas9) to develop crops and livestock with desirable traits. Genetically modified (GM) crops are among the most widely adopted and impactful applications in bio-breeding. China's cautious yet progressive approach to commercializing GM crops follows a stepwise "non-edible (e.g., cotton)—indirectly edible (e.g., animal feed like soybeans, corn)—directly edible (e.g., rice, wheat)" roadmap to ensure safety and public acceptance. To date, GM cotton, soybeans, maize, and papaya have been approved for commercial planting domestically. Initiated in 1998, China has cultivated GM cotton for nearly 30 years, and the adoption level exceeded 90% of the total cotton area since 2013. In recent years, the area has gradually fallen as the cultivation has moved to the west, and GM cotton still covered more than 77% of the total cotton area (AgbioInvestor, 2025). China has also made strides in commercializing GM soybean and maize. In 2021, GM soybean and maize were planted on 1150 mu (15 mu = 1 hectare), expanding to 80,000 mu in 2022 and reaching 4 million mu in 2023.

Biofertilizers are natural, eco-friendly substances that contain living microorganisms, which help plants absorb essential nutrients from the soil more efficiently (Khan et al., 2023). Biopesticides may be defined as any organism whose product or compound is applied to control populations of pests and parasites in a nontoxic and eco-friendly manner (Bilgrami & Khan, 2022). China's biofertilizer industry has expanded rapidly, with over 10,000 registered products, annual production exceeding 35 million tons, and a market value surpassing US$5.5 billion, reflecting China's commitment to greener farming practices (Sun et al., 2025). Similarly, the

biopesticide sector has gained momentum, with 71% of newly registered active ingredients (36 out of 51) classified as biological between 2019 and 2023 (NDRC, 2024). These statistics demonstrate China's strategic reorientation of its agricultural input regime, systematically replacing conventional chemical products with biological alternatives. The rapid scaling of biofertilizers and biopesticides forms a crucial component of China's broader bio-agriculture strategy, working in synergy with advanced bio-breeding programs to create a more productive, sustainable, and climate-resilient farming system.

The future focus of bio-agriculture is to enhance production and improve efficiency. By employing advanced techniques such as genome-wide selection, synthetic biology, and artificial intelligence, the goal of bio-agriculture is to develop high-yield and disease-resistant crops, as well as superior livestock breeds. Through the development of bioproducts such as biofertilizers and biopesticides, bio-agriculture will enhance the transformation into sustainable agriculture.

22.3.3 Biomanufacturing

Biomanufacturing is the process of using living systems, such as cells, microorganisms, or biological molecules, to produce useful products (Zhang et al., 2017). As one of the global leaders in biomanufacturing, China's biomanufacturing has an impressive annual growth rate exceeding 12% in recent years. The sector's remarkable scale is evidenced by its production of over 70 million tons of key bioproducts annually—including bio-fermentation products, bio-based fine chemicals, and advanced materials—generating more than 800 billion RMB in output value and supporting downstream industries worth over 1 trillion RMB (NDRC, 2024).

China dominates the bulk fermentation industry with an annual production exceeding 30 million tons, representing a market value of over 240 billion RMB and ranking first worldwide. In specialized market segments, China maintains substantial production shares, manufacturing 462,000 tons of yeast annually (about 30% of global capacity) and controlling 65% of fermented organic acid production globally (NDRC, 2024). China's biomanufacturing output not only satisfies substantial domestic demand across food, pharmaceutical, and industrial applications but also supplies international markets, significantly influencing global trade patterns. The sector's continued expansion into high-value applications through synthetic biology and precision fermentation technologies suggests China will maintain and potentially extend its leadership position in the evolving global bioeconomy.

The future of bio-agriculture lies in enhancing productivity and improving overall efficiency through the integration of cutting-edge technologies. Advanced approaches such as genome-wide selection, synthetic biology, and artificial intelligence are being leveraged to develop high-yield, disease-resistant crop varieties and superior livestock breeds. In parallel, the development and adoption of eco-friendly bioproducts—such as biofertilizers and biopesticides—are driving the transformation of agriculture toward more sustainable practices. These innovations collectively

aim to ensure food security, reduce environmental impact, and support resilient agricultural systems for the future. (Han et al., 2022).

22.3.4 Bioenergy

China is the world's largest consumer of fossil fuels, the leading importer of liquefied natural gas, the second-largest gasoline market, and the third-largest diesel market (IEA, 2023). In China, bioenergy contributes only a small proportion of its energy mix, but plays a critical role. In 2023, China ranked as the fifth-largest fuel ethanol producer, after the USA, Brazil, the EU, and India, accounting for just 3% of global production (RFA, 2024). However, with bioenergy potential representing 27.6% of China's energy consumption in 2016 (Kang et al., 2020), the country has significant untapped capacity.

China's bioenergy sector has demonstrated steady expansion, with fuel ethanol production showing significant progress. The installed fuel ethanol capacity reached 5.725 million metric tons annually by the end of 2023, primarily using corn, cassava, and some aging grain reserves as feedstocks. These outputs currently support an ethanol-gasoline blend ratio covering about one-fifth of China's total gasoline consumption. Notably, the country has achieved technological breakthroughs in cellulosic ethanol production, with second-generation biofuel output reaching 23,900 metric tons in 2023. The biodiesel industry, predominantly utilizing waste cooking oil and other waste lipids as raw materials, recorded production of 2.114 million metric tons in 2022. However, structural challenges persist, including suboptimal capacity utilization rates, hovering around 50% due to feedstock supply instability and limited domestic demand. Consequently, over 75% of China's biodiesel output is currently exported (NDRC, 2024).

The Chinese government has implemented a comprehensive policy framework to accelerate bioenergy adoption, including the 14th Five-Year Plan's target for non-fossil fuels to reach 20% of energy consumption by 2025 and the Biomass Energy Industry Development Plan (2023–2030), which focuses on agricultural waste utilization and biogas production. Key initiatives, such as the expansion of the E10 ethanol mandate and development of sustainable aviation fuels, demonstrate China's commitment to integrating bioenergy across multiple sectors. The country is also investing heavily in next-generation technologies, including cellulosic ethanol and algae-based biofuels, while addressing challenges related to feedstock supply chains and policy coordination. These efforts position bioenergy as an increasingly important component of China's renewable energy mix, supporting both environmental objectives and energy security goals, as the nation transitions toward a more sustainable development model.

The future focus of bioenergy includes biomass power generation and the transition to combined heat and power systems. Emphasizing research into new biomass technologies, it seeks to integrate biofuels with biochemical processes and improve anaerobic fermentation methods. The promotion of advanced biofuels in sectors

like transportation and municipal services is crucial for facilitating the shift from fossil fuels to renewable energy sources, contributing to a greener, more sustainable future.

22.3.5 Biological Environmental Protection

Biological environment protection is a multidisciplinary approach that integrates biotechnology and environmental protection to address ecological challenges and promote ecosystem health. This includes utilizing biological systems to develop biodegradable materials, enzyme preparations, and microbial inoculums that facilitate waste reduction and pollution control. Key practices in this field involve effective wastewater treatment through methods such as activated sludge processes and constructed wetlands, as well as managing organic solid waste, such as kitchen waste, crop straw, and livestock manure, through composting and anaerobic digestion. Additionally, biological environmental protection emphasizes strategies for habitat restoration and conservation, aiming for sustainable practices that ensure resource conservation and the efficient use of biological resources.

China's bio-environmental protection industry surpassed 2 trillion RMB in 2020, demonstrating remarkable growth in addressing ecological challenges. The sector's composition shows water pollution treatment as the dominant segment, accounting for over 50% of the market with a value exceeding 1 trillion RMB, reflecting escalating demand for advanced biological wastewater treatment solutions. In organic solid waste management, three primary streams have emerged as focal points: food waste, crop straw, and livestock manure. Projections indicate substantial market expansion potential, with the straw recycling sector expected to reach 70 billion RMB by 2025. Simultaneously, the annual volume of livestock manure requiring treatment approaches 1 billion tons, creating a projected market worth 139 billion RMB (NDRC, 2024). These figures underscore the growing importance of biological treatment technologies in China's circular bioeconomy strategy, particularly in transforming agricultural and municipal organic wastes into valuable resources. The rapid development of these sectors highlights China's commitment to integrating biotechnological solutions into its environmental protection framework while creating new economic opportunities.

Future biological environmental protection will aim to enhance environmental protection and pollution control by replacing traditional chemical processes with biomanufacturing technologies. This includes developing high-performance bio-environmental materials and bioproducts (e.g., bio-based polymers) that integrate biotechnology with key industries such as chemicals and pharmaceuticals, promoting a sustainable, low-carbon development model. The use of functional microorganisms and enzymes is encouraged for water treatment, soil remediation, and solid waste management, aiming to combat pollution in air, water, and soil (Gomes et al., 2020; Perera et al., 2023).

22.3.6 Bioinformation Industry

The bioinformation industry, which includes bioinformatics, big data in biology, and computational biology, helps to harness and analyze massive amounts of biological data. This is crucial for developing more efficient agricultural practices, improving healthcare through personalized medicine, and driving innovation in pharmaceuticals. By integrating information technology (IT) and artificial intelligence (AI) with biotechnology, the bioinformation industry accelerates research in genomics, proteomics, and systems biology, offering new solutions for environmental sustainability, bio-based industrial processes, and biotechnology innovation.

The development of China's bioinformation industry will focus on advancing R&D for major diseases like cardiovascular diseases, cancer, respiratory illnesses, and diabetes by utilizing AI and biomedical data to support decision-making processes. Additionally, it aims to develop life support and monitoring products, such as remote monitoring and wearable devices, and integrate technologies like 5G, blockchain, and the Internet of Things (IoT) to manage the full lifecycle of drugs and vaccines, establish traceability systems, and promote data sharing across healthcare platforms. The future also seeks to enhance "Internet + Healthcare" services, improving patient experiences with integrated online–offline medical services, expanding e-pharmacy options, and applying health data to research, clinical care, and elderly care to boost overall service quality.

22.3.7 Biomedical Engineering

Biomedical engineering supports the development of cutting-edge medical technologies, including medical devices, prosthetics, regenerative medicine, and tissue engineering. This has significant economic impacts by creating new industries, improving healthcare efficiency, and reducing costs in the long term. China has made huge progress in biomedical engineering, especially in medical equipment. In 2023, China produced the most SCI (Science Citation Index) publications, and over 70% of the global patent applications in medical equipment came from China, underscoring its leadership in this sector, which covers key areas such as medical diagnostics, surgical instruments, implantable devices, medical imaging, and computer-assisted surgery (NDRC, 2022).

China is enhancing its medical device regulatory framework by improving the priority approval policy, accelerating the medical device registrant system, and refining contract manufacturing management. China is also optimizing the allocation of innovation resources, streamlining review processes for innovative medical devices, and fostering international cooperation in medical device R&D. Additionally, the government is encouraging regional pilot programs to explore new regulatory models, aiming to create an efficient, innovation-friendly environment that

accelerates the availability of advanced medical technologies while ensuring high safety and efficacy standards.

22.4 Opportunities and Challenges

Building on the previous analysis, this section highlights the critical opportunities and challenges facing China's bioeconomy industries. On the one hand, rapid technological advancements and continuous regulatory reform will present significant potential for innovation and market expansion. On the other hand, global competitions, regulatory barriers, and public skepticism continue to hinder sustainable growth.

22.4.1 Opportunities

Policy support and strategic planning: As we discussed, China has demonstrated strong commitment to developing its bioeconomy through comprehensive policy frameworks and long-term strategic planning. The government will continue to offer substantial financial incentives to accelerate innovation in biomedicine, agricultural biotechnology, and industrial biomanufacturing. Provincial governments are also actively supporting bioindustrial parks and pilot zones, creating favorable ecosystems for startups. This top-down approach ensures coordinated development and helps China position itself as a global bioeconomy leader.

Growing demand for sustainable solutions: As China strives to meet its ambitious carbon neutrality targets—peaking emissions by 2030 and achieving net-zero by 2060—the demand for sustainable bio-based alternatives is surging. Biofuels, bioplastics, and bio-based chemicals are more widely used in industries such as energy and transportation. Additionally, stricter environmental regulations are pushing manufacturers to replace petroleum-derived materials with biodegradable and renewable alternatives, opening vast market opportunities for bio-based innovations.

New biotechnology innovation and breakthroughs: China is investing in cutting-edge biotechnologies such as synthetic biology, precision medicine, and gene editing to strengthen its global leadership in innovation, healthcare, and sustainable industries. The government is backing synthetic biology for bio-based materials and lab-grown products, advancing precision medicine through AI-driven genomics and CAR-T therapies, and promoting CRISPR gene editing for agriculture and therapeutics. Additionally, China is expanding into mRNA vaccines, neurotechnology (brain–computer interfaces), and microbiome research, supported by state funding, biotech hubs, and a booming startup ecosystem. These investments aim to enhance food security, medical breakthroughs, and green manufacturing while positioning China as a dominant force in the future bioeconomy.

22.4.2 Challenges

Global competitions: The biotechnology sector relies heavily on international cooperation, from joint research initiatives to shared supply chains for critical reagents and equipment. However, geopolitical rivalries are disrupting this ecosystem. For instance, the USA has imposed restrictions on Chinese biotech firms like BGI over data security concerns, mirroring earlier actions against Huawei in the tech sector. Meanwhile, China is accelerating its self-sufficiency drive, investing in domestic biomanufacturing capabilities to reduce reliance on foreign technology. These decoupling risks create parallel innovation systems, slow scientific progress, and increase costs for global health initiatives, such as pandemic preparedness and drug development.

Regulatory barriers: China's regulatory framework for GM crops is among the most stringent in the world, requiring extensive safety assessments before approval. While the government has greenlit GM cotton and papaya, staple crops like rice and wheat remain tightly controlled. This contrasts with the USA, where GM crops are widely adopted. China's caution stems from past food safety scandals (e.g., melamine-tainted milk) that eroded public trust, as well as geopolitical considerations—avoiding over-dependence on foreign seed companies like Monsanto. However, recent policy shifts suggest a gradual opening, with Beijing approving GM soybean and corn varieties in 2023 to boost yields amid rising food import costs (Xiao & Kerr, 2022).

Resource constraints: Scaling up bio-based production requires vast amounts of biomass, which could compete with food production. Ensuring a sustainable supply chain for feedstocks—such as crop straw—is a logistical challenge. Additionally, some bio-based processes still rely on energy-intensive methods, potentially offsetting their environmental benefits. Without circular economy approaches—such as waste valorization and carbon-efficient bioprocessing—China's bioeconomy growth could face bottlenecks.

Low consumer acceptance: Despite government promotion, many Chinese consumers remain unfamiliar with bio-based products. Cultural preferences for traditional materials and skepticism toward genetically modified foods hinder market adoption. To bridge the gap, the government has launched public education campaigns, but consumer resistance persists, with many preferring organic or traditional non-GMO products (Jin et al., 2022). This dichotomy highlights the challenge of balancing innovation with cultural and safety concerns.

22.5 Conclusion

China's bioeconomy is undergoing rapid transformation, driven by strong policy support, significant investments in biotechnology, and expanding market demand. The country has established itself as one of the global leaders across multiple

bioeconomy sectors, including biomedicine, bio-agriculture, biomanufacturing, and bioenergy. The government's strategic planning, particularly through initiatives like the *14th Five-Year Plan for Bioeconomy Development (2021–2025)*, has created a robust framework for sustained expansion. These policies emphasize technological innovation, environmental sustainability, and deep industrial integration across the biotechnology value chain, and could have a long-term impact on bioeconomy development.

China's bioeconomy presents immense opportunities, including policy-driven investment, growing demand for green solutions, and cutting-edge biotech innovations. However, challenges such as geopolitical tensions, regulatory hurdles, resource constraints, and public skepticism remain critical barriers. Addressing these challenges will require continued policy refinement, international collaboration, technological self-sufficiency, and public engagement to foster trust in bio-based solutions.

Looking forward, China is well-positioned to strengthen its global leadership in the bioeconomy through a balanced approach that combines market forces with policy guidance. By continuing to invest in research and development while improving commercialization pathways, China can translate its scientific achievements into economic and social benefits. International collaboration will remain important, particularly in areas like climate change mitigation and global health security. As China's bioeconomy matures, its success will increasingly be measured not just by economic output but by its contributions to solving global challenges and improving quality of life, both domestically and worldwide. This comprehensive development path promises to make biotechnology a cornerstone of China's high-quality development in the coming decades.

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Chapter 23
Circular Bioeconomy of Argentina's Fruits and Vegetables Agroindustry

Daniel S. Kirschbaum, Luis A. Polack, and Eduardo V. Trumper

23.1 Introduction

This chapter aims to present local scientific and technical experiences related to the circular bioeconomy of Argentina's FV agroindustry, but more specifically, cases involving native biological resources and those whose products or benefits return to the agricultural production system. Argentina produces more than 7 million tons of fruits (Navarro Villa, 2024) and about 8.5 million tons of fresh vegetables (Kirschbaum et al., 2024). The circular bioeconomy of the fruits and vegetables (FV) agroindustry in Argentina refers to the production and consumption of bio--based products from FV waste, minimizing their disposal and promoting sustainable resource use. The most important benefits of the circular bioeconomy of Argentina's FV agroindustry are waste reduction, lower greenhouse gas emissions, job creation and economic growth, sustainable resource use and conservation, and improved soil fertility and biodiversity.

One of the most ambitious goals of international food security policies is transforming agricultural systems to support growing global food demand. Such a

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process leads to reconfiguring these systems according to the circular bioeconomy model and designing interdisciplinary approaches that integrate bioeconomy with agroecology (Faucon et al., 2023). Circular bioeconomy in a broad sense involves using two strongly interrelated concepts: biotechnology and biological resources from various sources, to create an economic system in which bio-based products replace fossil fuel-based products in value chains, accentuating waste reduction and reuse, and utilizing other biological resources (Khanna et al., 2024). On the other hand, since the circular bioeconomy includes the revalorization of agri-food by--products to recover healthy biomolecules, and most crops are still conventional (pesticide-dependent), the reutilization of agri-food by-products might be subject to pesticide accumulation (Otero et al., 2023). To prevent this, synthetic agrochemicals usage should diminish, with bio-based inputs or strategies among the best choices (Priya et al., 2023). In this sense, biological control constitutes one of the various bio-based pest management tactics, usually considered an important piece of IPM programs (NIFA, 2024). Moreover, incorporating beneficial resident or indigenous macro and microorganisms, for both crop protection and plant growth promotion, reduces the requirements for water use, energy dependency, and reliance on synthetic agrochemicals, making farms more sustainable and less reliant on external inputs (Achillas & Bochtis, 2020). Adopting such native resources for pest biocontrol also brings other significant environmental benefits, such as reducing greenhouse gas emissions, in a frame of climate-smart agriculture. On the other hand, enhancing the action of locally occurring beneficial organisms, which are already adapted to local environmental conditions, would allow FV crops to better deal with biotic and abiotic stresses (Jennings et al., 2017; Sachdev et al., 2023), making these agricultural systems more circular and resilient.

In Argentina, sustainable intensification and adaptation of FV systems to climate change are approaches that have allowed growers to deepen and adjust the sustainable-based knowledge/technologies that are increasingly being available, such as biologicals, organic amendments, conservation tillage, direct sowing, service crops, green manures, biological control, and pollination, among others (Kirschbaum et al., 2024). Currently, FV growers are adapting their production technology to climate change and consumer demands (domestic and external). However, an issue of major concern for Argentinian FV growers is the continuous increase in fertilizers and pesticides, reducing farm profitability (Prosperi, 2024). On the other hand, due to the nutrient deficiency observed in FV production fields that were subjected to several decades of intensive soil utilization, and the consequent poor efficiency of chemical fertilizers, in-farm organic waste recycling for crop nutrient supply is becoming increasingly necessary, sustaining soil health, lowering pollution, and generating new job opportunities (Chatterjee et al., 2017; Dibella et al., 2021). Furthermore, an increasing number of FV processing plants and wholesale fresh markets are converting organic waste into compost and returning this organic matter to local orchards (Alurralde et al., 2021; CMCBA, 2021; Raimondo et al., 2023). These circular bioeconomy strategies are helping FV growers to be more independent of chemical fertilizers, reduce input costs, and sustain soil fertility.

23.2 Waste Use

23.2.1 Soil Improvers

23.2.1.1 Waste from Wholesale Fresh Food Markets

The present case is part of research conducted by Bruno (2023). Faced with the increase in waste volumes and the saturation of sanitary landfills in the metropolitan area of Buenos Aires (MABA), the treatment of organic solid waste gains importance. This fraction, besides being the most abundant, is also the simplest and most economical to deal with. Its use reduces the negative impact on the environment by inadequate final disposal and at the same time creates valuable products. Fruit and vegetable wholesale markets, which concentrate much of MABA's production, are strategic for the implementation of organic waste reuse projects, due to both the volume handled and the number of farms and retailers involved. Fruit and vegetable wholesale markets are defined as physical structures where commercial transactions are carried out with the physical presence of buyers, sellers, and produce (Senesi & Palau, 2015). However, these markets generally operate without accompaniment or regulation by the state and do not have waste management plans or information about the process. The complexity of the problem of organic solid waste management cannot be approached with linear and simplistic proposals. It is necessary to have quality information on the volume and fractions of waste generated by these markets, as well as to understand the logic and interactions of the human groups participating in these markets. The approach must be multidimensional, multidisciplinary, and intersectoral to give an integrated response. In line with this issue, in 2020, the Buenos Aires Central Market (Fig. 23.1), one of the largest wholesale fruit and vegetable markets in Latin America, initiated the Food Loss and Waste Reduction and Waste Recovery Program (Fig. 23.2) with the objectives of providing food suitable for human consumption, recovering organic waste through the production of compost and animal feed, and advising and training growers and operators on the management of waste losses and waste in the different stages of production, marketing, and consumption of food (CMCBA, 2021).

Wholesale fresh food markets often deal with organic solid waste that can be repurposed into fertilizer through various recycling initiatives (Jara-Samaniego et al., 2017; Mokjatturas et al., 2024). The supply of fruits and vegetables in Argentina involves multiple marketing channels, and is organized mainly in approximately 60 fruit and vegetable wholesale markets distributed throughout the territory (Bruno, 2023). Vegetable waste generated in these markets can be used for compost and organic fertilizer production and returned to nearby fruit and vegetable production areas. Only in the MABA, there are approximately 16,000 ha dedicated to fruit and vegetable production, involving around 7000 growers (Bruno et al., 2022). By implementing these experiences and initiatives, wholesale fresh food markets contribute to reducing waste, promoting sustainable practices, and supporting the local agricultural sector through organic fertilizer production.

Fig. 23.1 Warehouse of the wholesale area of the Buenos Aires Central Market. Credits: Corporación del Mercado Central de Buenos Aires

23.2.1.2 Waste from FV Industrialization Processes

Shifting from a linear to a circular management system has several advantages since fruit waste becomes a resource. Moreover, a circular management system leads to reducing greenhouse gas emissions. Natural soil improvers are among the major uses of fruit waste. The waste from the industrial transformation of various fruits (pomace) constitutes a source of nutrients (mainly potassium), water-soluble polyphenols, and organic matter for utilization in fruit and vegetable crops (Choudhury et al., 2021).

Argentina is the world's 11th largest producer of olive oil and the main producer and exporter in South America. Olive pomace is the main residue from olive oil extraction (Fig. 23.3). Each ton of processed olives generates around 800 kg of olive pomace (Rodríguez et al., 2022). This waste can be used as a soil amendment or organic fertilizer since it is rich in organic matter and nutrients (nitrogen, phosphorus, potassium) (García-Ruiz et al., 2012). Olive mill wastewater can also be used as a liquid fertilizer after appropriate treatment and nutrient balancing. Additionally, it can improve soil structure and water-holding capacity (Abu-Rumman, 2016). In Argentina, Alurralde et al. (2021) reported that the compost made from olive pomace mixed with pruning remains from olive groves is feasible for use as a substrate for vegetable seedling production.

Wineries are the main agroindustrial activity of the Argentinian province of Mendoza, generating a large variety of wastes, with depleted grape marc (DGM)

Fig. 23.2 Diagram of the Food Loss and Waste Reduction and Waste Recovery Program, implemented by the Buenos Aires Central Market. (1) Delivery of fruits and vegetables (FV) leaving the commercial circuit. (2) Separation at source. (3a) Food for packaging. (3b) Disposal of organic waste. ***3c.*** Disposal of inorganic waste. (4a) Transfer of pallets to the Community Action Area. (4b) Composting. (4c) Final disposal. (5a) Selection and re-classification of food. (6a) Delivery to canteens for immediate consumption. Credits: Corporación del Mercado Central de Buenos Aires

being one of them. Grape pomace (the solid waste from grape processing) can be composted and used as plant potting media, according to Pisi (2017), who studied the DGM composting process and its use in pure form or in mixtures to formulate substrates for flower seedlings. Composting of the DGM was carried out, in which various analyses, such as pH, CE, C/N, humidity, temperature, CO_2, granulometry, porosity, and density, were made on the initial material and during the process. Physical, chemical, and biological analyses were performed on the obtained compost. DGM proved to be an appropriate material for composting without the need to incorporate other components. The composting process lasted 160 days, and a compost with a low C/N ratio and CO_2 production, a slightly alkaline pH, low salinity, near-optimal total pore space, high aeration porosity, and low water retention capacity was obtained. The resulting substrate, with previous pH correction with micronized sulfur, was tested in petunia (*Petunia hybrida*), New Guinea impatiens (*Impatiens walleriana*), and French marigolds (*Tagetes patula*), with similar transplant growth parameters compared to a commercial substrate (Fig. 23.4).

Citrus industry by-products can be transformed into biofertilizers and returned to nearby lemon orchards, according to an experience carried out by an interdisciplinary group of researchers (chemists, physicists, and biotechnologists) from several

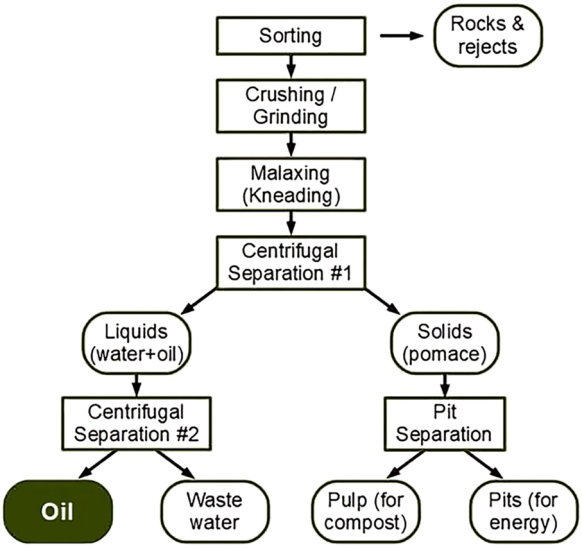

Fig. 23.3 Olive oil extraction flow chart. Credits: Slices of Blue Sky. Credits: www.slicesofbluesky.com

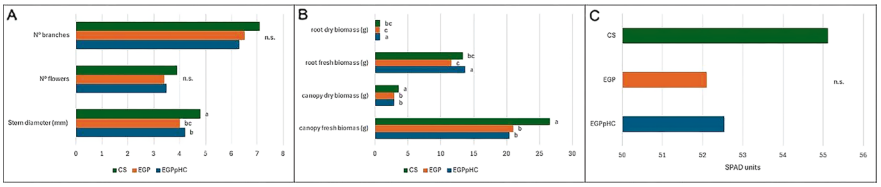

Fig. 23.4 Stem diameter, number of flowers and buds, number of branches, fresh aerial mass, dry aerial mass, fresh root mass, dry root mass, and leaf chlorophyll content of French marigold plants (*Tagetes patula*) grown in a substrate derived from the wine industry, in Mendoza (Argentina). Source: Prepared by the authors with data from Pisi (2017)

institutions, who developed a natural, microbiological composting accelerator or biocatalyst, representing a clear example of the circular bioeconomy (Raimondo et al., 2023; UNT, 2024). The innovative organic matter decomposition process consists of biomolecules developed in a laboratory, capable of speeding up the composting process from 120 days (without the biomolecules) to 45 days (with the biomolecules). The citrus industry by-products consist of fruits, pruning waste, by--products from juice extraction, and lemon peel. The obtained biofertilizer (Fig. 23.5) provides carbon and nitrogen to the soil, supporting lemon production. According to the authors, the developed biocatalyst could also be used with waste from other industries. The project took place in Tucumán (Argentina), and the research team involved belongs to the National University of Tucumán (UNT), the Pilot Plant of Microbiological Industrial Processes (PROIMI-CONICET), and the Environmental and Technological Interpretation Center (CIAT-Tafí Viejo Municipality).

Pear and apple production in Argentina is about 1.8 million tons, 78% of which corresponds to the province of Río Negro. Regarding apples, 60% are consumed

Fig. 23.5 Biofertilizer obtained from lemon processing by-products in Tafí Viejo (Tucumán, Argentina), ready to be re-utilized in lemon groves and other crops. Credits: Municipalidad de Tafí Viejo, Tucumán, Argentina

fresh and 40% go to the industry. For pears, these values are 72% and 28%, respectively. Of the fruit for processing, approximately 70% is used for concentrated juice production and 30% for cider broths and others. Solid waste generated by processed fruit represents 20–50% of the total volume of fruit, and its inadequate disposal can give rise to serious pollution problems. In the Patagonia region (Río Negro province, Argentina), Agüero et al. (2017) and Maldonado et al. (2021) developed options for the reutilization of wastes generated by pear and apple juice industries. The production of *Pleurotus ostreatus*, a lignocellulolytic fungus and edible mushroom, represents an important alternative for the use of that waste (uncomposted bagasse), rich in lignocellulose, a material that represents about 40% of the biomass produced by photosynthesis, and that cannot be used directly for human/animal food due to its low digestibility. Additionally, the final bagasse produced by the pear and apple juice industries as an organic amendment showed that it was viable for the growth of lettuce (*Lactuca sativa* L.) and tomato (*Solanum lycopersicum* L.), and foxtail millet (*Setaria italica* L.), with promising positive results. This demonstrated that the composted waste could be used as an organic amendment and replace peat in transplant production.

23.2.1.3 Waste from FV Production Processes

There are strong arguments for nutrient recycling, which means more use of organic nutrient sources within horticulture. It is possible to recycle surpluses and at the same time improve the supply of energy and provide nutrients and carbon for

agricultural production. This trend has promoted the characterization, management, treatment, and agronomic valorization of waste generated in agricultural systems, allowing the final product to have a higher biological and environmental value than the mere use of raw organic matter.

Bokashi, an organic fertilizer that is increasingly gaining popularity in agriculture, is the result of a composting technique developed in Japan based on the addition of a liquid solution of anaerobic bacteria and lactic acid yeasts (Vicente et al., 2020). As described by Dibella et al. (2021), bokashi is a fertilizer made from the semi-decomposition of organic waste (Fig. 23.6). The microorganisms that exist in the waste itself produce, under controlled conditions, a material that is capable of fertilizing plants and at the same time nourishing the soil. One of the main functions of bokashi is to add a great diversity of microorganisms (bacteria, fungi, yeasts) to the soil to enrich it. In this way, it is possible to generate healthy and strong plants, capable of better protecting themselves against pathogens.

Anzorena et al. (2020) evaluated the effect of the addition of bokashi to a commercial substrate on the length of the leaf in lettuce seedlings at the time of the transplant, the time of permanence in the nursery, and the weights achieved at harvest. The experiment was carried out in seedling trays with commercial substrate as the control and the addition of 5% and 25% bokashi. The transplanting was carried out in plots in a greenhouse. The treatments using commercial substrates with added bokashi significantly improved the quality of the lettuce seedlings and the time to planting of the seedlings was reduced. In addition, these effects had a positive effect on the crop, with better yields.

Garlic is a species with nutraceutical properties cultivated in Córdoba (Argentina), which is especially important due to its beneficial effect on human health, and as a raw material for biologicals used to manage potential pests. Current garlic cultivation in Córdoba depends on nitrogen fertilization with chemical synthesis products. Ávila et al. (2023) evaluated the effect of bokashi on garlic yield. Three garlic

Fig. 23.6 Monitoring temperature during the bokashi production process. Credits: Dibella et al. (2021), INTA IPAF Cuyo, San Juan, Argentina

cultivars (Alpa Suquía; Pampeano, and Serrano) planted in the soil were biofertilized with bokashi, along with an unfertilized control. In two of the three cultivars used, Serrano and Pampeano, bokashi generated higher crop yield. The bulbs harvested in the biofertilization treatments showed higher weight in both Serrano and Pampeano cultivars, and a greater proportion of bulbs of large diameter.

23.2.2 Agroindustry By-Products as Biopesticide Sources for Crop Protection

Agroindustry residues are materials derived from the processing of agroforestry industry products. However, these industries are increasingly concerned with reducing the environmental impact of the waste generated, including antioxidant phenolics recovered from agricultural by-products (Mourtzinos & Goula, 2019). Polyphenols are secondary metabolites of plants, commonly involved in defense against biotic or abiotic stresses (Stiller et al., 2021).

Potato is a functional food with significant amounts of antioxidant polyphenols such as phenolic acids, flavanols, and anthocyanins. It is currently the third most important food crop worldwide. In Argentina, there are important potato processing companies that produce large volumes of peel waste, which has no value-added destination. Under crop quality standards, industrial potatoes produce clean waste, consisting of clean and healthy peel/skin, obtained by steam peeling. McCain, a world leader in processed potatoes, produces 75 $t.day^{-1}$ of waste in Argentina, 365 days a year, which makes a total of 27,000 $t.year^{-1}$ that are destined directly to feedlots for cattle. Silveyra et al. (2019) characterized the profile of phenolic compounds and determined the biological activity of antioxidant polyphenols from industrial potato waste on the phytopathogenic fungus, *Fusarium solani*. They determined that potato skin (peel) has 2–4 times more polyphenolic compounds than the pulp, as well as greater antioxidant activity. They also found a significant decrease in the germ tube length, probably associated with a decreased spore germination rate, indicating a putative fungistatic effect. These findings convert potato tuber skin waste into a valuable material with prospects for developing plant biofungicides.

23.3 Biotechnology

23.3.1 Native Biological Resources as Tools for FV Pests and Diseases Control

23.3.1.1 Biological Control of FV Arthropod Pests

There is a worldwide trend to reduce the use of chemical products, due to the harmful effects on the environment and human health, as well as the appearance of resistance. The *Beauveria* genus presents the most common cosmopolitan insect pathogenic fungi and parasitizes more than 700 insect species. Additionally, different *Beauveria* species can produce organic acids, such as oxalic and citric acid, which change the pH of the medium by releasing inorganic phosphorus. *Beauveria bassiana* can establish itself as an endophyte in leaves, stems, and roots by inoculation of leaves or soil, promoting higher germination rates and biomass accumulation, and native strains of this beneficial fungus have demonstrated biocontrol capacities, as an entomopathogen, like those of commercial synthetic biocides on insect pests (Barra-Bucarei et al., 2020). Plants treated with *B. bassiana* significantly reduced population levels of several FV pests such as two-spotted spider mite (*Tetranychus urticae*), *Lygus* bug, and phytophagous beetles, without affecting beneficial mites (Sabbahi et al., 2008; Canassa et al., 2019). Native *Beauveria bassiana* colonies were first isolated in Tucumán, Argentina, from the soybean pest *Rhyssomatus subtilis* (Coleoptera: Curculionidae) (Allori Stazzonelli & Yasem de Romero, 2016). More recently, different *Beauveria* isolates obtained from *Drosophila suzukii* were shown to have enthomopathogenic activity against this invasive dipteran frugivorous pest (Ledesma et al., 2024) in laboratory experiments (Fig. 23.7). Currently, all these *Beauveria* isolates are being genetically characterized and tested against different horticultural crop pests in Argentina.

The moth *Cydia pomonella* (L.) causes severe damage to pome fruit and walnut trees in the different producing regions of the world. In Argentina, it is the main pest in apple, pear, walnut, and quince crops. Broad-spectrum synthetic insecticides are used to control *C. pomonella*. Native strains of entomopathogenic fungi isolated from soil samples taken from apple and walnut orchards of La Plata (Argentina) were evaluated against larval stages of *C. pomonella* under experimental conditions by Castello et al. (2020). For the pathogenicity tests, two strains of *Metarhizium anisopliae* (Metschnikoff) Sorokin and two *Beauveria bassiana* (Bals.-Criv.) Vuill. strains (CEP 229 and CEP 436) were used. *Cydia pomonella* larvae, from the second and fifth stages, were used as target insects. After application, the treated larvae were transferred to Petri dishes and fed. Mortality was monitored daily during the first 10 days after application. Both *M. anisopliae* and *B. bassiana* were pathogenic for the larval stages of *C. pomonella*. In all cases, more than 70% mortality was recorded in second instar larvae. Mortality was lower for fifth instar larvae (50%). Native strains of *M. anisopliae* CEP 679 and CEP 682 were the most pathogenic for second instar larvae of *C. pomonella*, causing 96.6% and 100% mortality,

Fig. 23.7 Adult of *Drosophila suzukii* (spotted-wind Drosophila) infested by *Beauveria* sp. under laboratory conditions in Tucumán, Argentina. Credits: Ledesma et al. (2024), INTA Famaillá, Tucumán (Argentina)

respectively. The strain that caused the lowest percentage of mortality was CEP 229 of *B. bassiana* (73.3%). It is concluded that the strains of entomopathogenic fungi isolated from soil are potentially microbial biological control agents of *C. pomonella* in fruit trees.

Allograpta exotica is a fly native to the Neotropics belonging to the family *Syrphidae* (Insecta: Diptera). Adults, like the rest of the hoverflies, are excellent pollinators (Fig. 23.8), but in this species, the larva is a predator of arthropod pests, mainly aphids, and is found naturally in horticultural crops (Maza et al., 2022). In the Neotropics, hoverflies are not commercially available, and this species has been studied in Argentina by an interinstitutional research group since 2013 to the present, as a predator of different pests such as aphids (*Myzus persicae*, *Chaetosiphon fragaefolii*), whiteflies (*Bemisia tabaci*), thrips (*Frankliniella gemina*), and spider mites (*Tetranychus urticae*) (Díaz Lucas et al., 2024; Maza et al., 2024a), which are primary pests of pepper and strawberry crops. However, these harmful phytophagous species are widely polyphagous, affecting several fruit and vegetable crops not only in Argentina but also worldwide. In preference trials conducted in Argentina, *A. exotica* larvae prefer aphids to thrips at the L1 and L3 larval stages (Maza et al., 2024a). Releases of immature stages of the hoverfly were also carried out to control

Fig. 23.8 Adult of the hover fly *Allograpta exotica*, whose larvae are small insect pests predators, feeding on a strawberry flower in Tucumán, Argentina. Credits: Noelia Maza (Facultad de Agronomía, Zootecnia y Veterinaria. Universidad Nacional de Tucumán, Argentina)

Chaetosiphon fragaefolii, the strawberry aphid (Díaz Lucas et al., 2024), with promising results. This hoverfly is promising for mass rearing and use in augmentative biological control of pests such as aphids, thrips, and whiteflies (Maza et al., 2023).

Native parasitoids are potential tools for the biological control of invasive exotic pests, such as the frugivorous flies spotted-wing drosophila, *Drosophila suzukii* Matsumura, and African fig fly, *Zaprionus indianus* Gupta (both Diptera: Drosophilidae). Following biological invasions, the establishment of exotic species may be restricted, among other things, by their susceptibility to native or established natural enemies. The Neotropical-native pupal endoparasitoid *Trichopria anastrephae* Costa Lima (Hymenoptera: Diapriidae), although primarily associated with hosts of the genus *Anastrepha* (Tephritidae), has also been described as attacking Drosophilidae (Buonocore-Biancheri et al., 2024). Native to Argentina, *T. anastrephae* has been shown to control frugivorous drosophilid flies under laboratory conditions (Funes et al., 2024), where the infestation degree index was 100% in *D. suzukii* and 38% in *Z. indianus*, and the parasitism success was 48% for both drosophilids. These findings indicate that the native parasitoid *T. anastrephae* has a high potential as a biocontrol strategy against *D. suzukii*, and to a lower degree against *Z. indianus*, both invasive frugivorous flies spread in Argentina (Escobar et al., 2018).

23.3.1.2 Biological Control of FV Diseases

Trichoderma is a cosmopolitan and opportunistic genus of ascomycete fungi that includes species of interest in agriculture as direct biological control agents of phytopathogens (Woo et al., 2023). This beneficial fungus can improve the growth and development of various plant species safely and sustainably, including combating both biotic and abiotic stress, which impair the normal development of plants, causing crop losses (Abdullah et al., 2021). *Trichoderma* uses direct antagonism and competition, particularly in the rhizosphere, where it modulates the composition and interactions with other microorganisms. In its colonization of plants, in the roots, or as an endophyte, *Trichoderma* has developed the ability to communicate with the plant and produce numerous benefits for its host. This complex plant-microorganism association ranges from its capacity as a growth promoter to its ability to induce local and systemic defense responses to biotic and abiotic stress (Sood et al., 2020). Thus, its potential as a biocontrol agent (mycoparasitism; Vero et al., 2023), biostimulant, and biofertilizer makes it attractive in sustainable agricultural approaches. Several *Trichoderma* spp. strains native to Argentina were efficient in controlling pathogenic fungi in beans, blueberries, and strawberries (Allori Stazzonelli et al., 2017; Achával & Meneguzzi, 2022).

The fungal pathogen *Neopestalotiopsis clavispora* is the causal agent of root and crown rot, an emerging disease that causes severe damage to strawberries in Argentina, which cultivates about 2000 ha and produces approximately 70,000 t of strawberries (Maza, Kirschbaum, et al., 2024b). *N. clavispora* was identified in Argentina in 2016, causing serious losses in commercial strawberry fields (Obregón et al., 2018). The symptoms on leaves are reddish-brown interveinal spots that expand to cover the entire leaflet, which coincide with necrotic areas and discoloration in roots and crowns and can cause plant death. In a laboratory study aimed at evaluating biological alternatives for controlling this disease (Ramallo et al., 2024), dual cultures were performed in Petri dishes with glucose potato agar medium, confronting mycelial discs of *N. clavispora* with two strains of *Trichoderma* (the local INTA strain, and *T. asperellum*) independently. *Bacillus methylotrophicus* was also included in the test. The average inhibition values were 61.1% for *B. methylotrophicus*, while both *Trichoderma* strains, native and commercial, showed greater inhibition of 90%, indicating that both *Trichoderma* strains (Fig. 23.9) were highly antagonistic to *N. clavispora*. When inoculated into strawberry plants, *Trichoderma* increased plant fresh and dry weight, and root length (Ramallo et al., 2024). The results indicate that preventive management with *Trichoderma* could be an efficient strategy to reduce the damage caused by *N. clavispora*, taking care of the quality and safety of the fruit and preserving the biodiversity of the agroecosystem in strawberry-producing areas.

Fig. 23.9 Effect of two isolates of *Trichoderma* on the development of the strawberry pathogen *Neopestalotiopsis clavispora*. Nc: *Neopestalotiopsis clavispora*; T INTA: *Trichoderma* "INTA"; T asp: *Trichoderma asprellum*. Credits: Ana C. Ramallo (Facultad de Agronomía, Zootecnia y Veterinaria. Universidad Nacional de Tucumán, Argentina)

23.3.2 Native PGPR and Abiotic Stress Reduction

Azospirillum is an alpha proteobacterium that belongs to the order *Rhodospirillales* and the family *Azospirillaceae* (Baldani et al., 2015) and is naturally present in the soil, from where it colonizes plant roots. This genus is part of the well-known Plant Growth-Promoting Rhizobacteria (PGPR), which are a group of bacteria capable of improving plant performance through various mechanisms, such as biological nitrogen fixation and hormone production, among others (Saad et al. 2020). In addition, these bacteria can improve plant tolerance to different diseases (Fujita et al., 2017; Viejobueno et al., 2021). They currently have a biotechnological use as an inoculant, commonly applied to seeds during sowing to improve crop production (Seleiman & Abdelaal, 2018). For example, it has been reported that inoculation of wheat (*Triticum aestivum* L.) seeds with *A. brasilense* improved their productivity and nitrogen use efficiency (Gaspareto et al., 2023). Furthermore, this bacterium increases both root and foliar biomass, improving water and nutrient uptake (Cassán et al., 2020; Oliveira et al., 2022; Ramallo et al., 2024). In recent exploratory studies, the ability of the *A. argentinense* (ex *brasilense*) REC3 strain (isolated in Argentina) to attenuate the negative effects of thermal stress (due to high temperatures) in strawberries has been reported (Ruiz Domínguez et al., 2023), and to increase root yield in sweet potato (Saccone et al., 2021).

23.4 Renewable Energy-Enhanced FV Production

The bioeconomy seeks to diminish reliance on fossil fuels, reduce climate change, and efficiently use resources (Perišić et al., 2022). Nowadays, renewable energy sources account for 14% of the total primary energy supply, with biomass as the largest renewable energy source globally at 10%, followed by hydropower at 2.5% and other renewables (solar, wind, geothermal, tidal, etc.) at 1.5% (Popp et al., 2021). Renewable energy sources play a very important role in reducing the amount of greenhouse gas emissions generated by burning fossil fuels (Boccard, 2013; Nemet, 2013). Successful experiences in the desert and windy Argentinian Patagonia demonstrate the feasibility of these clean energy technologies for producing fresh food in hostile climates. This is the case of "Strawberries of the Wind," a sustainable production project co-financed by the European Union, which promotes the development of rural communities through renewable energy, technical training, and agroecological strawberry production in Argentina (The 500RPM Foundation, 2024).

The Strawberries of the Wind project aims to transform the arid and almost unproductive Patagonian steppe region of Chubut, Argentina, into an epicenter of horticultural production. It seeks to boost the development of rural communities through a combination of renewable energy, technical training, and strawberry production. Promoted by 500RPM, a non-profit organization, and Argentina's National Institute of Agricultural Technology (INTA) in the Chubut province, Strawberries of the Wind implements wind (Piggott, 2014) and solar energy to provide access to electricity and water in isolated rural areas. It works with different water pumping systems, drip irrigation, and production under low tunnels to promote efficiency and crop protection (Fig. 23.10). Reported fruit yields in Patagonia under this system are within a range of 600 to 800 g per plant for a biennial crop (Mora & Ivars, 2019).

The project also focuses on capacity building, offering technical training to family farmers to grow and market high-quality strawberries. In addition, it encourages the training of qualified local labor through the manufacture of wind turbines in technical schools (United Nations Development Programme, 2024). It promotes multi-sector and multi-actor coordination with active participation of rural communities, municipalities, local institutions, and public and international organizations. Despite the highly adverse environment, farmers make a significant contribution, successfully bringing local fresh and healthy fruit production to nearby markets.

23.5 Conclusion and Future Directions

On the one hand, there is a great dynamism, capacity, and willingness on the part of the science and technology sector to undertake new challenges. However, greater coordination should exist between industries, fruit and vegetable producers' needs, local governments, and academic and scientific institutions. On the part of the business sector, there should be greater awareness of the environmental impact of the

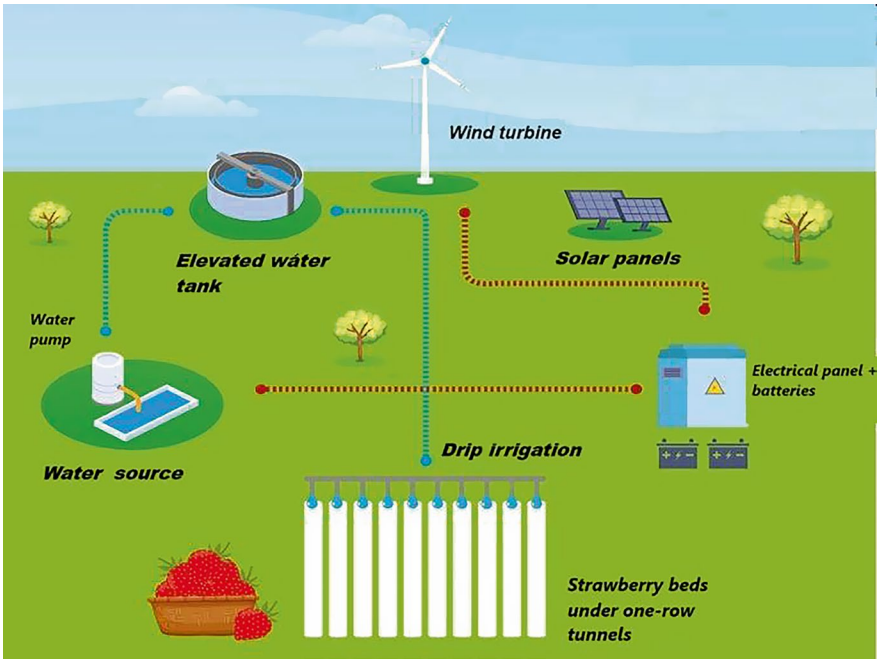

Fig. 23.10 Functional diagram of the Wind Strawberries project, Argentina. Credits: Eduardo E. Miserendino (INTA Esquel)

waste it generates and the obligation to process it and add value to it in a circular bioeconomy scheme. There should also be more proactive public policies aimed at the circular bioeconomy of the fruit and vegetable industries. It would be essential to have an updated survey of the experiences underway, build a database of the experiences and human resources involved, and create a bank of ideas. Having private funds to finance circular bioeconomy projects in the fruit and vegetable chain would help stimulate more progress in this matter.

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Chapter 24
The Case of Sustainable Dairy Production Model

Alejandro López Moriena and Martina Zibell

24.1 Introduction

In recent years, the concept of circular bioeconomy has become a central topic in discussions among governments, companies, and communities around the world. Unlike traditional linear systems, circular bioeconomy models promote a sustainable approach where resources are reused and repurposed while offering a practical and forward-thinking solution for long-term sustainability. The implementation of this type of production model contributes to the minimization of waste generation and thereby the environmental impact.

For the agribusiness industry, the concept of circular bioeconomy holds particular significance. Agriculture is inherently resource-demanding, requiring water, energy, land, and raw materials. As global populations rise and the scarcity of natural resources increases, agribusinesses are continuously adopting more and more sustainable practices to maintain productivity and profitability. By integrating circular principles, companies can reduce waste, enhance resource efficiency, and foster resilience in their supply chains. Whether it's through reducing effluents or creating value from agricultural by-products, circular bioeconomy offers a path toward a more sustainable and prosperous future for agribusiness.

It could be argued that the dairy sector is one of the most important food industries, offering a wide range of milk-based products like yogurt, cheese, and butter, among others. However, like any industry, it has a considerable environmental impact. So, how can agribusiness companies adopt strategies that enable them to produce sustainably while taking care of the environment?

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24.2 Adecoagro: Developing Sustainable Production Models

Adecoagro is a Latin American company specialized in the production of food and renewable energy. Since 2011, the company has been listed on the New York Stock Exchange (NYSE) under the ticker AGRO. With more than 560 thousand hectares of land under management in Brazil, Argentina, and Uruguay (Fig. 24.1), Adecoagro produces a wide range of products including sugar, ethanol, renewable electricity, cereals, oilseeds, rice, and dairy products of high quality. Its diverse products are sold in both domestic and international markets.

At Adecoagro, our culture is marked by entrepreneurship and continuous improvement. Therefore, we enhance our competitive advantages by developing and adopting technologies that enable us to produce our diverse product portfolio. Our dairy business is a prime example of what we are trying to convey. Considering our cows not only produce milk but also generate organic matter, adopting technologies to manage manure efficiently is crucial. We have implemented innovative solutions to convert waste into electricity and biofertilizers. At the same time, we are constantly seeking to incorporate new technologies that can optimize the processes. For instance, we've used software to monitor the health of our cows, ensuring their welfare is prioritized. This continuous improvement approach extends to our dairy plants as well, as we aim to achieve enhancements not only in our fields but also throughout our industrial processes.

We pay special attention to each of our customers' needs, generating integration in all aspects of our value chain. While carefully controlling the quality and safety of our food, we coordinate the logistics of our products and offer product traceability to meet the demands of different markets. For instance, ensuring the quality and safety of our milk is a key priority in our dairy business. To support this, we

Fig. 24.1 Adecoagro's operations. *Source*: Adecoagro, 2024 Integrated Report

regularly perform shelf-life tests and microbiological analyses at our Chivilcoy and Morteros plants, aiming to enhance export flexibility while maintaining a strong focus on food quality and safety.

Our geographic diversification, the wide variety of products we offer, and our focus on achieving efficiencies throughout the whole value chain are some of the strengths that make us stand out from the rest of the companies in the industry. But above all, we focus on what we do best: producing food and renewable energy while carrying out sustainable and efficient dairy production systems.

Since our origins, we have understood sustainability from a three-dimensional perspective that combines economic, environmental, and social aspects. Our sustainable way of business operation allows us to constantly evaluate the balance between our operations and the environment with a long-term vision. We are convinced it is possible to produce while taking care of natural resources, implementing regenerative agricultural practices, and focusing on the integration and support of local communities. This is clearly demonstrated in our dairy production processes, where we aim to build robust food and renewable energy value chains that can meet the demands of our growing and diverse customer base. Our goal is to become a leading provider of carbon credits while decarbonizing our operations in alignment with the global climate agenda.

24.2.1 How We Approach Sustainability

Sustainability is located at the center of the strategy of Adecoagro's business. This allows us to address the environmental, social, and economic challenges of each region and operation, while strengthening the strategies for sustainable dairy development.

At our crop fields, for example, we apply "No-till Farming," which allows us to reduce the risk of erosion, increase the productive potential of our soils, and improve the infiltration of rainwater. This technology consists of leaving crop plant residues on the surface of the soil after harvesting a crop. Other benefits of implementing this practice include the increase in soil organic matter content, the reduction of the use of inputs (such as fertilizers, fuels, and phytosanitary products), and sustainable yields over time. Other sustainable agriculture practices adopted by Adecoagro are land-leveling, crop rotation, cover crops, among others. These practices support regenerative agriculture, which makes sustainable use of the soil, improves both soil quality and productivity, and provides feed to our cows.

The social pillar plays an essential role in the sustainability strategy of Adecoagro. To reinforce our commitment to managing and minimizing any type of risk, all of our employees are covered by our occupational health and safety management system at our freestalls and in our dairy plants under the international standards, such as the International Labor Organization (ILO) standards

and ISO 45.001 guidelines, particularly in Argentina. We also emphasize our compliance with the health and safety legislations of each country in which we operate. In addition, we seek to contribute to the development of the communities where we operate. We adopt the best practices for stakeholder engagement and facilitate local development through various programs, projects, and donations. We focus on supporting local communities, as most of our employees come from these areas, where their social lives and families are rooted. For example, we generate renewable electricity for the local grid.

At Adecoagro, we are convinced that the economic pillar is key when making decisions. That's why, whenever we consider a new project for implementation within our processes or operations, the economic factor is always a central part of the discussion. Specifically, when evaluating the adoption of new technologies or engaging with start-ups and innovation-driven companies, we focus on analyzing the economic proposal and ensuring it aligns with our environmental and social strategies.

24.3 Rethinking Sustainability: What We Mean When We Talk About Circular Economy?

From the very start, nature has followed the principle of circularity (Stahel, 2019). As a food and renewable energy company, we have adopted this mindset since our beginnings.

When we started our dairy business, we wanted our production model to be sustainable over time. That's why our approach seeks to preserve soil health, use water resources appropriately, maintain representative samples of the most important ecosystems, avoid pollution, and generate renewable energy from the by-products of our operations while recycling or reusing most of the waste that we generate.

The Ellen MacArthur Foundation (Wijkman & Skånberg, 2016) refers to circular economy as a

> a regenerative system in which resource input and waste, emissions, and energy leakages are minimized through long-lasting design, maintenance, repair, reuse, sharing, remanufacturing, refurbishing, and recycling activities.

This definition is key in the approach we have at Adecoagro because we use the by-products generated in each production model to reuse them in other stages of the process. Our dairy business is a clear proof of this concept. Our biodigesters obtain biogas from cow manure, which is then used to generate bioelectricity through power generators. The bioelectricity is injected into the local grid, and the organic matter remaining from the process returns to the fields as biofertilizer for the crops sown for cow feed. You now may be wondering, how this system works?

24.4 Effluent Management and Renewable Energy Generation in Dairy Farms

24.4.1 Tracing Our First Steps

At Adecoagro, sustainability is part of our DNA. In fact, more than 87% of the energy we consume is self-generated and renewable. In our dairy farms, we developed a production model where manure is used to generate electricity with our biodigesters.

Our dairy business includes 4 high-productivity farms that operate at full capacity and maintain elevated productivity rates. Our farms located in Christophersen, in the province of Santa Fe (Argentina), house approximately 14,400 milking cows. This is our main competitive advantage compared to traditional dairy farms. Currently, the average dairy farm in Argentina has around 250 cows. Smaller farms often rely on manual systems with limited technological integration. At Adecoagro, we firmly believe that technology is essential to continuously improve our processes. For example, we are evaluating the incorporation of robotic arms during the milking process, which would allow us to be faster and more precise, while maintaining our high standards of animal welfare, quality, and productivity.

Each one of our 14,400 cows produces almost 38 liters of milk per day, "which represents a much higher value than the national average" (Ámbito Financiero, 2024). This is not only due to the incorporation of various technologies that allow us to be increasingly efficient, but also because we implement animal welfare practices to help our cows reach their full productive potential. This factor should not be overlooked. In our company, promoting the overall welfare of the animals is a priority. We work every day to ensure their health and comfort, focusing on guaranteeing that everyone at our facilities treats the animals with care. Our production models integrate this pillar as essential to continue producing more and better over the years. To adhere to these principles at our facilities, we are guided by our animal welfare program and policy (Adecoagro, n.d.-a, b, c). In 2022, we received an animal welfare certification from the International Agricultural Organization (OIA, for its initials in Spanish), for all our milking cows. Nowadays, to continue upholding the highest standards of animal welfare, we are currently updating and reviewing our internal animal welfare protocol to ensure the completion of this certification. This certification guarantees that the milk is obtained from herds that have been raised and managed with respect for animal welfare. In fact, this means that 100% of the milk produced in our dairy farms is animal welfare certified. From comfortable spaces to a balanced diet sourced from our own crops, we ensure that our cows are healthy and comfortable.

Along with the same idea, to maximize the performance of our cows while maintaining high standards of animal welfare, we closely monitor their feed intake. Our cows are housed in freestalls at all times and are milked three times a day. As previously mentioned, our dairy operation is based on an efficiency model supported by

the application of good agricultural practices. This model allows us to reduce supply risks by producing most of the feed we need on our own fields.

Furthermore, our use of no-till farming, crop rotation, and cover crops enhances resilience against climate variability. We also apply biofertilizers derived from our dairy's biodigesters, reducing our reliance on chemical fertilizers. Being located in the heart of the humid Pampas in Argentina—with strong local availability of feed—further minimizes potential supply risks.

Since this dairy journey began, we have always focused on implementing efficient and sustainable technologies that serve as a long-term solution for our business. To address peak energy demands during the summer season, we have installed solar panels in our dairy farms. Our San Gregorio Solar Park features 1,550 solar panels that power fans and sprinklers to ensure our cows remain comfortable and cool during hot weather. With an installed capacity of over 0.5 MW, our solar energy park has generated more than 2,300,000 kWh of renewable energy since it began operating.

Moreover, keeping in mind that our cows produce a large amount of milk, we must also take into account that each of them generates manure. This presents a significant challenge, given that we have 14,400 cows on our farms. This is where our circular dairy model (see Fig. 24.2) starts to make more sense. As a result, when we started

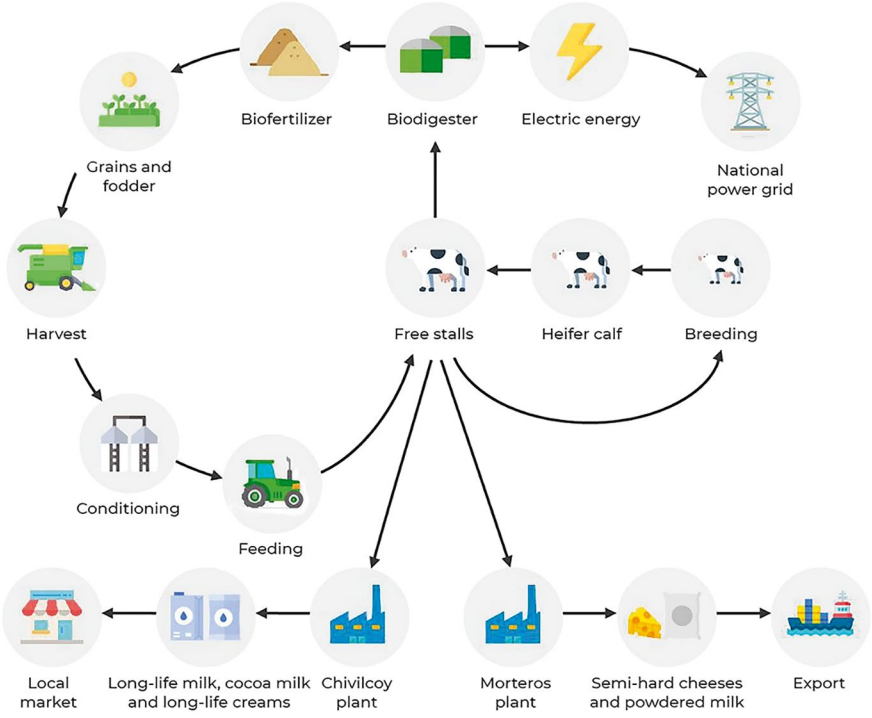

Fig. 24.2 Adecoagro circular dairy model. *Source*: Adecoagro Sustainability website

Fig. 24.3 The first biodigester in our freestalls. With a diameter of 30 meters and a height of 6 meters, it presents a substantial structure. *Source*: Adecoagro Institutional website

developing our dairy business, we began to search nationally and internationally for different practices and technologies, both in the dairy industry and in other industries, that would allow us to better manage the effluents generated. Consequently, we decided to invest over USD 6 million in the construction of the first biodigester in our freestalls 1 and 2 (see Fig. 24.3). This biogas plant, which began operating in 2017, has already processed more than 400,000 tons of cow manure and generated over 50,000 MWh of renewable energy (Adecoagro, 2024). At the same time, by processing such a large amount of cow manure and converting the biogas into bioelectricity, we avoid significant quantities of greenhouse gas (GHG) emissions. This is because biogas is a fuel highly concentrated in methane, and by capturing and using it to produce bioelectricity, we are able to drastically reduce emissions.

24.4.2 How Our Biodigesters Work?

Under a circular bioeconomy model, we collect all the manure from our cows and use it as input for our biodigester. Under controlled conditions of temperature and moisture, specific microorganisms break down the organic matter and thus release biogas with a high content of methane.

On the one hand, a by-product of this process is biogas. Through a treatment process and the use of power generators, we convert this fuel into electricity. All the electricity we generate is sold and fed into the local power grid. By contributing to the grid, we not only improve our own energy stability—avoiding micro-outages and voltage drops—but also help nearby communities achieve more reliable electricity and reduce power outages. This is especially important to us, as it creates

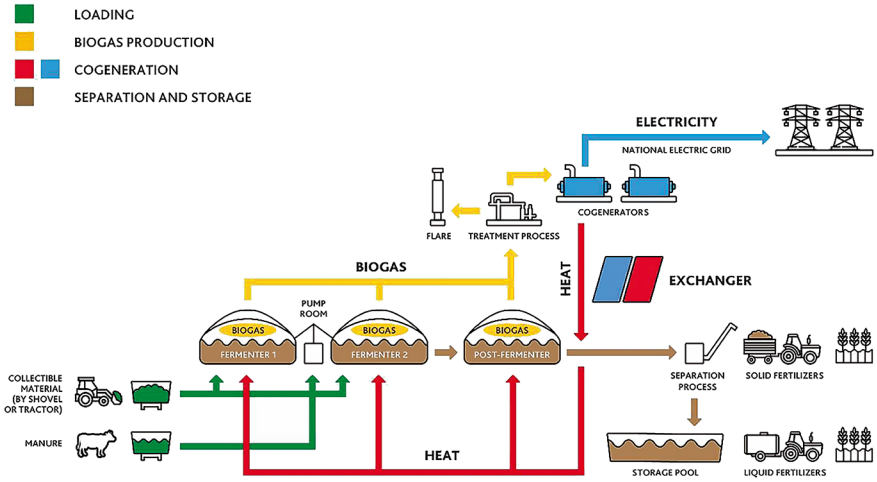

Fig. 24.4 How our biodigesters work. *Source*: Illustration adapted by Adecoagro

value not only for our operations but also enhances the quality of life for our employees living in neighboring towns.

On the other hand, in our biodigesters we transform the remaining organic matter from this process into biofertilizer for the crops that will later serve as feed for our cows, thus completing the production cycle. Thanks to the implementation of these biofertilizers, we not only reduce the use of agrochemicals but also improve soil carbon (see Fig. 24.4). In other words, the biodigester digestate and its liquid manure fraction are used as biofertilizer on our crop fields, which are later harvested to feed our cows. This practice helps reduce greenhouse gas emissions associated with the use of crop protection products. In 2024, we were managing 100% of our cow manure through two biodigesters, generating bioelectricity and avoiding over 38,000 tCO_2e per year.

By implementing this system, we place special emphasis on efficiency and quality. This results in high raw milk production, which is then processed by our industries and transformed into value-added products sold in both domestic and export markets.

Even though this text focuses on our dairy production model, it is important to highlight that our sugarcane business, with operations in Brazil, also has a biodigester. This unit produces biogas which is then cleaned and processed to be transformed into biomethane. We use this biomethane as fuel for our vehicles and machinery in the sugarcane operations. On top of that, in our Sugar, Ethanol, and Energy business, we generate electricity from sugarcane, processing by-products, such as bagasse. The electricity we generate in our cluster meets our own needs, and the surplus—around 65% in 2023—is sold to the grid (Adecoagro, n.d.-a, b, c). In fact, we are one of the largest exporters of bioelectricity in the industry, with a production equivalent to an amount sufficient to supply a city of almost one million inhabitants.

24.4.3 Boosting Renewable Energy Generation

To keep driving our production models toward greener and more efficient systems, we inaugurated our second biodigester for freestalls 3 and 4, making an investment of more than USD 8 million to develop our second and larger biogas plant.

This new biodigester was mainly designed by our own teams based on the know-how acquired from our first biodigester and the experience gained with our sugarcane business' biodigester. The entrepreneurial spirit of our teams led them achieve improvements, such as an installed capacity of 2 MW and an energy generation potential of 17,500 MWh per year. On top of that, with our new biodigester operating, we now have the potential to generate around 25,000 MWh annually that are directly injected into the local grid (Adecoagro, 2024).

24.4.4 Producing Milk with a Positive Impact

The core of our dairy business is to produce high-quality milk while creating a positive impact on both people and the environment. The launch of our second biodigester represents a significant step forward in our sustainable, integrated, and traceable production system. This USD 8 million investment complements the more than USD 176 million we have invested over the past 15 years to improve sustainable milk production and strengthen local economies. Through projects like this, we foster collaboration with multiple stakeholders, including our teams, suppliers, government entities, and local organizations such as police, firefighters, schools, and others. All these partners joined us at the inauguration ceremony to celebrate this important sustainable milestone (see Fig. 24.5).

Our sustainability approach is reflected in our highly recognized dairy brand, "Las Tres Niñas" (The Three Girls in English). We produce our milk with a triple-impact purpose. That's why we have established three pillars that guide us in our continuous improvement journey toward greater sustainability: (1) sustainable dairy farming, (2) milk sourced from our own dairy farm, and (3) our cows' welfare. Since 2019, with the acquisition of two industrial plants located in Chivilcoy (Buenos Aires Province, Argentina) and Morteros (Córdoba Province, Argentina), we have committed ourselves to offering a premium product that reflects the sustainable way in which we do things. All the products that comprise our portfolio (see Fig. 24.6) are crafted using cutting-edge technology to ensure safe and healthy milk that can be stored for long periods of time. The brand offers five varieties of long-life milk and holds a 10% share of the UHT milk market in Argentina. At the same time, Las Tres Niñas is one of the few Argentinian dairy brands that owns a dairy farm. This differential keeps quality at the center in every part of the process, from cow milking until the product reaches the shelf, ensuring the minimum packaging time after milking (Agrositio, 2024). "Las Tres Niñas" is positioned as an innovative and honest brand of the highest quality.

Fig. 24.5 Our second biodigester's opening ceremony. *Source*: Adecoagro Institutional website

Fig. 24.6 Our product family. *Source*: Adecoagro, 2024 Integrated Report

24.5 Conclusion and Future Directions

To conclude, Adecoagro's innovative approach to dairy production serves as a compelling example of how circular bioeconomy principles can be effectively integrated into the agribusiness sector, especially in dairy production. By transforming waste into valuable resources through biodigesters and employing regenerative agricultural practices, Adecoagro not only enhances its operational efficiency but also contributes to a more sustainable food system. This chapter highlights the vital importance of adopting sustainable production models in an era marked by resource scarcity and climate change. The commitment to balancing economic, environmental, and social dimensions within Adecoagro's operations serves as a holistic approach to sustainability that is crucial for the future of agriculture.

As the agribusiness industry deals with increasing demands and environmental pressures, Adecoagro's practices highlight the potential for circular bioeconomy models to drive resilience and profitability as a long-term solution. This case study serves as a call to action for other agribusinesses to rethink their production processes, fostering a shift toward more sustainable practices that benefit not only the industry itself but also the communities and ecosystems involved. Ultimately, the path to a sustainable future lies in embracing innovative solutions that prioritize both resource efficiency and environmental care.

As a final reflection, we believe that the main barrier or challenge to carrying out this type of project is financing. Considering these models require significant capital investment, not every producer—such as the traditional dairies mentioned earlier—has access to the necessary resources. On the other hand, we believe that knowledge is a key factor. While it can be acquired at varying costs, this asset is often more accessible than financing. Anyone who immerses themselves in these topics can implement them, as long as they have the necessary dedication. In any case, we believe that once these barriers are overcome, this model is fully scalable.

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Chapter 25
Circular Sociobioeconomy in the Amazon: Grassroots Innovation for Sociobiodiversity Products

Michel Xocaira Paes, João Vitor Campos-Silva, and José Antonio Puppim de Oliveira

List of Abbreviations

BE	Bioeconomy
CBE	Circular Bioeconomy
CBM	Circular Business Models
CE	Circular Economy
CG	Collaborative Governance
CSBE	Circular Sociobioeconomy
CUs	Conservation Units
FUNAI	National Foundation for Indigenous Peoples
GHG	Greenhouse Gas
IBAMA	Environment and Renewable Natural Resources
ICMBio	Chico Mendes Institute for Biodiversity Conservation
INCRA	National Institute for Colonization and Agrarian Reform
IP	Indigenous Peoples

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IPLC	Indigenous Peoples and Local Communities
LCs	Local or Traditional Communities
NGOs	Non-Governmental Organizations
PAEs	Agroextractive Settlement Projects
PGPMBio	Policy for Minimum Price Guarantees for Sociobiodiversity Products
PNAE	National School Feeding Program
PRONAF	National Program for Strengthening Family Agriculture
RDS	Sustainable Development Reserve
RESEX	Extractive Reserve
SBE	Sociobioeconomy
SDGs	Sustainable Development Goals
SEMA	State Department of the Environment

25.1 Introduction

25.1.1 The Amazon as a Stage for New Economic Approaches

In light of the climate crisis, biodiversity loss and socioeconomic inequality, new development models are being debated, constructed, and implemented worldwide. As an alternative to the linear economy (of extraction, production, use, and final disposal), which is based on the consumption of fossil and non-renewable natural resources (such as sand for glass production, ores for metal production, oil for plastics, and other fossil fuels for energy production), the theories of Circular Economy and Bioeconomy emerge as important alternatives to the prevailing model of the last century (Taron & Gebrezgabher, 2024). However, the sociocultural context that operationalizes Circular Bioeconomy (CBE) needs to be considered, which we call Circular Sociobioeconomy (CSBE). CSBE is essential for considering alternatives for a more sustainable future for the Amazon.

The Amazon is globally recognized for its immense biological and cultural diversity, housing thousands of species of fauna and flora, as well as being home to hundreds of Indigenous Peoples and Local Communities (IPLC) (Levis et al., 2024). However, this wealth faces constant challenges due to the predatory exploitation of natural resources, deforestation, and climate change. Conserving this diversity is complex, as it involves not only the protection of ecosystems but also the respect and appreciation of the knowledge and cultural practices of local populations, which in turn play a fundamental role in maintaining a balance between the ecological and social systems (Levis et al., 2020).

Bioeconomy emerges as a promising solution for the conservation of ecosystems by promoting the sustainable use of biological natural resources (Bugge et al., 2016). It proposes an economic development model that values biological resources and biodiversity, by transforming sustainably produced forest products for the market and making ecosystem services into sources of income for local communities. Moreover, the sociocultural processes that directly interact with the bioeconomy,

particularly in the Amazon, which we call sociobioeconomy, are essential for strengthening the sustainability of the bioeconomy. This approach, grounded in the sociocultural roots of those who have lived in the territory and have maintained its sustainability for centuries, can create incentives to keep the forest standing and improve the quality of life for its inhabitants. It generates sustainable economic opportunities without compromising the functioning of ecosystems, while also strengthening the autonomy of communities, their culture, and their role in territorial management (Abramovay et al., 2021).

The circular economy complements the sociobioeconomy perspective. It promotes the integration of productive chains, product development, waste reduction, and material reuse, creating a sustainable cycle of production and consumption (Mancini et al., 2021). The Circular Economy (CE) has the following main objectives: a) to keep products and materials at their highest level for as long as possible; b) to eliminate waste from the outset and design (through product design); and c) to regenerate natural systems (Ibn-Mohammed et al., 2021; Morseletto, 2020; Suavé et al., 2016). Traditionally, the theory and practice of CE have been approached from different perspectives, through technical and biological cycles, and across different levels (micro, meso, and macro) (Moraga et al., 2019; OECD, 2021).

These initiatives can reduce environmental impacts and externalities, while also promoting jobs and economic growth (EMF, 2015; Kirchherr et al., 2017; Paes et al., 2019). In the Amazon context, they can be essential to reduce environmental impact in a sensitive environment by reusing resources and minimizing the exploitation of new materials (Paes et al., 2021). This aligns with the need to conserve local biodiversity, promoting practices that not only preserve the environment but also generate economic value from waste and by-products, creating a virtuous cycle for the region (Paes et al., 2021).

25.1.2 Sociobioeconomies (SBEs): Bioeconomy in the Amazon Context

Bioeconomy (BE) has been defined as all sectors and systems that depend on biological resources (for example, plants, animals, microorganisms, biomass, and organic waste) and their functions and principles (such as ecosystem services) (Christensen et al., 2022). Therefore, it interlinks land use, natural resources, and ecosystem services with all economic and industrial sectors that utilize these biological resources to produce food, products, and bio-based energy (European Commission, 2018). BE has also been developed and worked on through three perspectives or narratives: biotechnological bioeconomy, bioresource bioeconomy, and bioecological bioeconomy. The latter concerns productive systems where the criterion of sustainability takes precedence over the unilateral growth of the economy (Bugge et al., 2016; WRI, 2022). These concepts are presented in detail in Sect. 25.3 (The Circular Sociobioeconomy).

Initiatives promoting bioeconomic perspectives for sustainable development seem to be the major bets for a better future in the Amazon (Abramovay et al., 2021). Regardless of the concept used, there is no clarity regarding the (i) role of Indigenous Peoples and Local Communities (IPLC) in these arrangements, (ii) how the benefits and costs will be distributed, especially for IPLC, and (iii) how the bioeconomy projects can truly ensure biodiversity protection in the Amazon. Therefore, the design of a new Amazonian Bioeconomy concept that takes into account the cultural diversity, cosmologies, epistemologies, social dynamics, and conservation needs is imperative for the future of the region.

Grassroots movements have advocated for a broader concept of bioeconomy, called sociobioeconomy. Amazonian sociobioeconomies are based on the sustainable use of biodiversity and restoration of forests and rivers to support the well-being, rights, and territories of Indigenous Peoples and Local Communities (Garrett et al., 2024). These economies combine activities that conserve multifunctional landscapes and cultural diversity while adding economic and social value to the region's biodiversity. This includes the conservation of ecosystems and the development of biodiversity-based value chains in light of traditional knowledge, developed over millennia (Levis et al., 2024). Traditional knowledge is the set of information acquired by Indigenous Peoples and traditional communities through their experience with nature and observation and experimentation of procedures and results. This knowledge came from the need to adapt to the environment in which they live, the wisdom of their ancestors, and the exchange of this knowledge with other peoples and communities. This knowledge is part of their way of life and daily routine, even when only one person in the community holds it (IPHAN, 2024).

However, despite their essential role in safeguarding ecosystem services, the families and communities responsible for these efforts often benefit the least from current Amazonian economic models. Moreover, the "socio" of the sociobioeconomy highlights the importance of the social dimension of sustainable development in the bioeconomy. This approach challenges the dominant bioeconomy models based on commodities with short-term high returns, disembedded from the local social and ecological context, which have long contributed to poverty and the overexploitation of resources in the Amazon. Therefore, sociobioeconomies offer a sustainable and equitable alternative to traditional economic structures. Rather than focusing on missed profits from deforestation or unsustainable river infrastructure, policymakers are encouraged to recognize the lost opportunities for inclusive development by not investing in sociobioeconomies. A coordinated mix of policy interventions is urgently needed, including stopping activities that harm forests and rivers, protecting the rights of Indigenous Peoples, creating participatory processes for designing sociobioeconomies, and developing financing mechanisms and logistics to boost demand for bioeconomy products (Garrett et al., 2024).

In bioeconomy arrangements (or sociobioeconomy, in the case of the Amazon), resources are already naturally circular (Vanhamäki et al., 2020). A circular bioeconomy can be developed through practices such as the cascading use of bioresources, the treatment and reuse of organic waste, the connection of material and energy flows in productive systems, as well as the development of bio-based

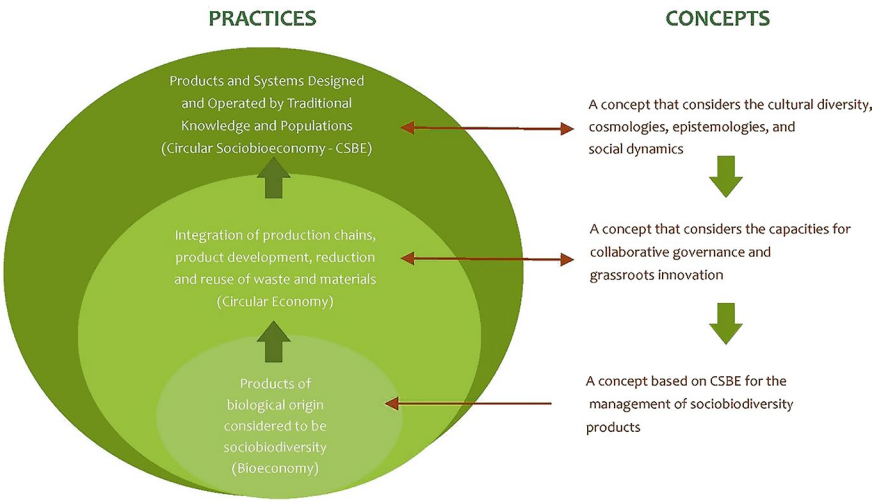

Fig. 25.1 Integration between the practices and concepts of the bioeconomy, circular economy, and circular sociobioeconomy

products and technologies (Paes et al., 2021). Thus, it is understood that the concepts of circular economy and bioeconomy overlap to some extent, with Circular Bioeconomy being the intersection of these two concepts (Muscat et al., 2021). As this study considers the social aspect to be intrinsic to the bioeconomy, a model will be presented here that integrates the concepts and practices of (socio)bioeconomy and circular economy, referred to as Circular Sociobioeconomy—as shown in Fig. 25.1. The Brazilian Amazon has emerged as an important territory for the development of the CSBE model, which can serve as an alternative model to counter the predatory approaches that are also encroaching on this region.

In this chapter, we analyze the challenges and opportunities for the development of the Circular Sociobioeconomy in the Brazilian Amazon, exploring how successful case studies of bioproducts have contributed to biodiversity conservation and the promotion of socioeconomic development in the region. These cases include two biodiversity-based value chains: collaborative management (co-management) of the Pirarucu (Arapaima gigas), the world's largest freshwater fish, and the use of andiroba and murumuru seeds to produce oils for cosmetics.[1]

This work makes important contributions by (1) introducing the concept of Circular Sociobioeconomy (CSBE), (2) identifying the activities that promote CSBE and how they are connected with the biological cycle (of CE) and the bioecological bioeconomy; (3) understanding how grassroots organizations are organized to

[1] The studies, findings, and reflections that underpin this chapter have been developed since 2019 by the authors through fieldwork and a comprehensive literature review, which includes both scientific literature and consultations of official documents and reports from governments and institutions focused on Circular Bioeconomy in the Brazilian Amazon.

operationalize CSBE; (4) bringing reflections and debates about what the main local challenges are and what learning can be expanded to the Brazilian Amazon and to other locations that have similar characteristics; and (5) presenting future directions for public policies, community-based initiatives, studies, and scientific research.

25.2 Socioecological Context of Amazonian Sociobioeconomy

The region known as the Amazon Rainforest encompasses the vast basin of the Amazon River, the largest river basin on the planet. It consists of 25,000 km of navigable rivers, spanning six countries (Bolivia, Brazil, Colombia, Ecuador, Peru, and Venezuela) (Brazil, 2024a). In Brazil, this region is part of what is officially referred to as the "Legal Amazon," which includes nine states (Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, Roraima, Tocantins, and part of Maranhão) and 775 municipalities. This territory covers just over five million square kilometers (approximately 61% of Brazil's territory) and has a population of 29.5 million inhabitants (13.7% of Brazil's total population), with about 70% residing in urban areas and 30% in rural areas (IBGE, 2024). Despite the challenges and needs of urban and infrastructure policies for these regions, these cities and urbanized areas serve as important and potential consumer centers for sociobiodiversity products, as well as locations for the storage and distribution of these products.

If it were a country, the Legal Amazon would be the sixth largest country in the world by land area. This region represents 67% of the world's tropical forests, with one-third of the trees and 20% of the freshwater on the planet (Imazon, 2013). Within this region, there are also various protected areas, Indigenous Lands, and maroon settlements from agrarian reform (Brazil, 2024a; IBGE, 2024). Due to all this grandeur, both territorial and demographic and cultural, the processes of land management, monitoring, and economic development in the region face challenges. As a result, predatory activities have advanced for decades or even centuries in this territory. Examples include deforestation for illegal timber sales, land occupation for cattle ranching, and the consequent land grabbing. Mining and gold panning are also other growing predatory activities that are difficult to contain (Haddad et al., 2024). However, there are also various activities focused on community and sustainable management of the forest and products considered part of sociobiodiversity. Examples include a myriad of fruits, seeds, and fish, including açaí, andiroba, babaçu, baru, extractive rubber, buriti, extractive cacao, Brazil nuts, juçara palm hearts, macaúba, mangaba, murumuru, pequi, piaçava, pinhão, managed Pirarucu, and umbu (CONAB, 2023; Garrett et al., 2024).

25.2.1 Policies to Incentivize Amazonian Sociobioeconomy

Public policies are fundamental for strengthening sociobioeconomies in the Amazon, as they create the necessary framework to promote the sustainable use of natural resources under fairer market relationships. These policies can protect the rights of Indigenous Peoples and traditional communities, ensuring their leadership in territorial management and biodiversity preservation. Additionally, the development of financing mechanisms, infrastructure, and tax incentives is crucial for stimulating the production and consumption of bioeconomy products, generating sustainable and equitable economic opportunities (Campos-Silva et al., 2021). At the same time, policies that combat predatory activities, such as deforestation and river degradation, are essential for preserving the ecosystems that support these economies. For example, the current Brazilian government has several initiatives in the area of sociobioeconomy (see the link: https://www.gov.br/secom/en/latest-news/2024/07/productive-forests-program-to-foster-food-production-reforestation). Thus, coherent and collaborative public policies are indispensable for transforming sociobioeconomies into viable development alternatives for the Amazon.

The Brazilian federal government has established the Policy for Minimum Price Guarantees for Sociobiodiversity Products (PGPMBio), which ensures a minimum price for 17 extractive products that aid in the conservation of Brazilian biomes (CONAB, 2023). Through this policy, the Federal Government purchases directly from producers or rural producer cooperatives the products covered by the PGPM, paying the guaranteed minimum price if the market price falls below the announced minimum price (Schwantes & Bacha, 2019). The PGPMBio aims to promote environmental conservation, reduce deforestation, minimize the effects of climate change, and ensure employment and income for traditional populations with their forms of social organization. These communities occupy and utilize territories and natural resources as a condition for their economic sustenance and cultural, social, religious, and ancestral reproduction, using knowledge, innovations, and practices generated and transmitted through secular tradition (CONAB, 2023).

Another important program for this sector is the National Program for Strengthening Family Agriculture (PRONAF), which is aligned with the federal government's Ecological Transformation Plan (PTE) and aims to promote agroecological production, the adoption of sustainable agricultural practices, and the encouragement of healthy food production through differentiated credit conditions and a record volume of financial resources. Among the innovations of the new PRONAF, launched in July 2024, are reductions in financing and operating interest rates (ranging from 0.5% to 6% per year, indicating negative real interest), the existence of ten credit lines (two for operating costs and eight for investments), and a total of R$ 76 billion for the next 2 years (Brazil, 2024b). Among the credit lines, four are highlighted as related to the value chains under study: (i) *Pronaf Agroindustry:* for the processing, storage, and marketing of agricultural, extractive, artisanal, and forest products; also supports the development of rural tourism; (ii) *Pronaf Bioeconomy:* financing for investments in renewable energy technologies,

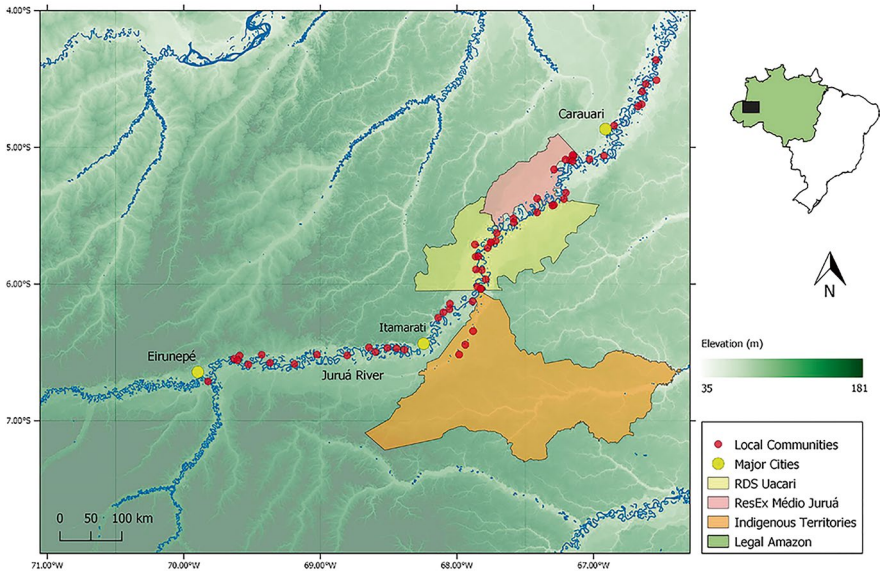

Fig. 25.2 Location of the municipality of Carauari (Middle Juruá region) in Latin America, Brazil in the state of Amazonas

environmental technologies, water storage, forestry, and the adoption of conservation practices aimed at soil recovery and enhancement of productive capacity; (iii) *Pronaf ABC+ Forest:* finances activities related to the implementation and management of agroforestry systems; ecologically sustainable extractive exploration, management plans, and forest management; restoration and maintenance of permanent preservation areas and legal reserves, and recovery of degraded areas; and (iv) *Pronaf Agroecology:* financing for agroecological or organic production systems, including costs related to the establishment and maintenance of the enterprise. Although these policies are comprehensive, they still face limitations due to the constraints of the Brazilian state, low local technical capacity, and the lack of specific financing and infrastructure for the region (Levis et al., 2020).

Nevertheless, some territories and regions have been considered models of community-based innovation regarding the management of biodiversity products (Campos-Silva et al., 2021), such as the Médio Juruá Region, located in the municipality of Carauari (which covers an area of 25,778 km^2 and has a population of 28,742 inhabitants) in the state of Amazonas (IBGE, 2022) (see Fig. 25.2). The communities studied in this location (which engage in seed collection, oil production activities, and Pirarucu co-management) are situated within two sustainable use protected areas (Uacari Reserve and Médio Juruá Extractive Reserve). These cases demonstrate how these initiatives can serve as examples for bioeconomy and circular economy projects—known as Circular (Socio)bioeconomy.

25.3 The Circular Sociobioeconomy (CSBE)

As highlighted in the Introduction, Circular Economy is divided into technical and biological cycles and has been studied and developed at three levels and scales—micro, meso, and macro. The micro level is more related to the development of circular processes and products, the meso scale pertains to industrial symbiosis, neighborhoods, cities, and even regions, while the macro scale relates to broader territories (such as states, countries, and continents) beyond global value chains (Moraga et al., 2019; OECD, 2021).

From the perspective of the biological cycle, the main activities that encompass this cycle are related to the use of raw materials and renewable natural resources, the reuse of waste and inputs through cascading and/or biological treatment (composting and anaerobic digestion), the regeneration of the biosphere (such as degraded soils and ecosystems), and fishing, aquaculture, agriculture, and collection (such as using biodiversity products from native forests) (EMF, 2015; Kirchherr et al., 2017; Paes et al., 2024). As seen, there is a natural alignment between the approaches of sociobioeconomy and circular economy, which, if well-structured, can substantially contribute to creating conservation opportunities and improving the quality of life in the Amazon.

Bioeconomy, as previously mentioned, has been studied and implemented through three different perspectives and concepts—biotechnological bioeconomy, bioresource bioeconomy, and bioecological bioeconomy (Bugge et al., 2016). Unlike CE, bioeconomy often presents divergent and conflicting applications that are not necessarily aligned or complementary with the cycles and levels of CE. A comparison of the multiple definitions of bioeconomy adopted in Brazil and abroad by different sectors and regions reveals how the term can sometimes signify quite distinct ideas—such as large-scale monoculture activities, on one hand, or sustainable management of native forests, on the other—for different interest groups and scientific perspectives. As presented in a literature review (Bugge et al., 2016; Vivien et al., 2019), the prefix "bio" carries much ambiguity. These different perspectives on bioeconomy can be distinguished based on four criteria: a) Adherence to basic objectives to sustainability or economic growth; b) Main strategies for generating economic surplus; c) Main vectors, drivers, and mediators of innovation; and d) Spatial approach (technological, agricultural, and urban fields (Bugge et al., 2016).

The biotechnological bioeconomy primarily aims for economic growth and job creation, with sustainability criteria being a secondary consideration (Bugge et al., 2016). This subordinate condition of the environmental criterion presented by the authors stems from the implicit hypothesis that the incorporation of science-intensive technologies in the production process contributes to environmental efficiency. Being more intensive in high-tech scientific processes, it is assumed that these technologies and the economy are more environmentally efficient and, consequently, sustainable.

The bioresource bioeconomy is guided by the need to seek a greater balance between the growth and sustainability of products and processes (Bugge et al.,

2016). It is based on the introduction of product innovations derived from nature, which are the main source of economic surplus creation: innovation in natural materials; sustainable management and good extractive practices; reduction and utilization of waste; and cascading use of the same raw materials. Like the biotechnological pathway, the bioresource pathway is directly dependent on scientific research and development but adopts a broader perspective regarding research fields. Here, interaction and collaboration among intermediary sectors of value chains, bringing together different competencies, become fundamental elements. There is a less linear view of the research-science-development-consumption process compared to the biotechnological perspective, yet it remains demanding in terms of costs and focused on the business and scientific realms.

The bioecological bioeconomy, on the other hand, addresses the production and economic systems based on the premise that sustainability criteria and indicators should form the foundation, countering unilateral economic growth. This represents an alternative paradigm to the two previous cases, as the creation of economic surpluses depends on processes that prioritize the promotion of sociobiodiversity, conservation of ecosystems, the ability to provide ecosystem services, and prevention of soil degradation. In these processes, the reuse and recycling of waste and the reduction of external inputs for each production system are adopted as strategies to create systems with intense internal circulation of matter, energy, and economic value (Bugge et al., 2016).

Most stakeholders would interpret CBE as the intersection between the two emerging concepts—circular economy and bioeconomy. However, the relationship between circular economy and bioeconomy is considered complex and is a continuous and ongoing debate (Tan & Lamers, 2021). The European Commission's bioeconomy strategy interprets CBE as a framework to reduce dependence on non-renewable natural resources; transform manufacturing; promote the sustainable production of renewable resources from land, fishing, and aquaculture; and encourage their conversion into various bio-based products and bioenergy, while also creating new jobs and industries (European Commission, 2018).

In Brazil, two important laws were published in 2024: the National Circular Economy Strategy (Brasil, 2024c) and the National Bioeconomy Strategy (Brasil, 2024d). However, there is still no specific public policy for CBE, even though there is a strong convergence of the aforementioned themes and laws, as will be shown next. Thus, some guidelines of the National Circular Economy Strategy can be highlighted, such as the elimination of pollution and reduction of waste generation; maintenance of material value; environmental regeneration; reduction of dependence on natural resources; sustainable production and consumption; extension of the life cycle of all materials; and ensuring a just, inclusive, and equitable transition that addresses gender, race, ethnicity, and socioeconomic disparities (Brasil, 2024c).

Among the guidelines of the National Bioeconomy Strategy, the following can be emphasized: promoting economic and productive activities that support sustainable use, conservation, regeneration, and valuation of biodiversity and ecosystem services; decarbonizing production processes and promoting biomass production and processing systems; fostering bioindustrialization; encouraging regenerative agriculture, productive restoration, recovery of native vegetation, and sustainable

forest management and production, especially of healthy food systems; respecting the rights of Indigenous Peoples and traditional communities and the traditional use and management of their territories; expanding and improving the innovation environment based on biodiversity assets, agricultural and forestry production; professional training and capacity building, promoting entrepreneurship and job creation; encouraging research activities, technological development, innovation, and production; fostering collaboration among federal entities and between the public, private, and academic sectors and civil society; and promoting forest and sociobiodiversity economies, increasing the participation and income of Indigenous Peoples, traditional communities, and family farmers (Brasil, 2024d).

Authors highlight that a circular bioeconomy can be simply interpreted as the more efficient management of renewable biological resources, integrating circular economy principles into the bioeconomy (D'Amato et al., 2018). The debate on the relationship between circular economy and bioeconomy can also be summarized in any of the following five relationships: (1) circular economy and bioeconomy as separate but reinforcing; (2) both concepts as completely integrated; (3) both concepts as partially antagonistic; (4) bioeconomy as a prerequisite for circular economy; or (5) circular economy as a tool for transitioning from a fossil economy to a bioeconomy (Leipold & Petit-Boix, 2018). Furthermore, some authors argue that bioeconomy is inherently "circular by nature," as it operates based on the renewable and circular characteristics of ecosystems and biodiversity (Leipold & Petit-Boix, 2018). For example, bio-based products derived from renewable biological carbon (the main component of biological compounds such as biomass) are recycled and reused through the biosphere (i.e., the carbon cycle).

As an alternative to the conventional concept of bioeconomy, the term SBE places social and climate justice as a central value. Therefore, it seeks to combine inclusive local development with the protection of the knowledge, rights, and territories of Indigenous Peoples (IP) and local or traditional communities (LCs), including settlements of afro-descendants (Science Panel for the Amazon, 2021). SBE promotes restorative justice by prioritizing the ethical normative values of Indigenous populations captured in the concept of *buen vivir* (good living), which highlights the intrinsic relationships between nature and people in local ecosystems and the need to safeguard biological, cultural, and social diversity (Science Panel for the Amazon, 2021). These value-based approaches are recognized in the federal constitutions of Bolivia, Colombia, Ecuador, Brazil, and Peru. Finally, SBE aims for distributive justice by prioritizing (re)investments and budget increases in health centers, education, infrastructure, and food distribution for rural and urban people, including revitalized urban economies with manufacturing and service industries that add value to products derived from nature-based solutions in SBE, to better serve most of the Amazonian population (Garrett et al., 2024; Torres et al., 2015).

Therefore, the concept of CSBE can contribute to more sustainable development, including collaboration toward some of the Sustainable Development Goals (SDGs) defined by the United Nations (United Nations, 2022), as can be seen in Table 25.1. However, one of the major social and scientific challenges is to demonstrate how innovation processes can occur to create CSBE. Thus, the following section will

Table 25.1 The potential of the CSBE in the Amazon and its relationship with the SDGs

The potential of the CSBE	SDGs that can be achieved and benefited
Job and income generation	SDG 1: Ending poverty in all its forms
Food security	SDG 2: Ending hunger, achieving food security and improved nutrition, and promoting sustainable agriculture
Quality of life for local communities	SDG 3: Ensuring healthy lives and promoting Well-being for all
Training for the population	SDG 4: Ensuring inclusive and equitable quality education and promoting lifelong learning opportunities for all
Women's empowerment	SDG 5: Achieving gender equality and empowering all women and girls
Local economic development	SDG 8: Promoting sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all
Promotion of infrastructure and Agroindustries	SDG 9: Building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation
Reduction of regional inequalities in Brazil	SDG 10: Reducing inequality within and among countries
Improvements to rural settlements and communities	SDG 11: Making cities and human settlements inclusive, safe, resilient, and sustainable
Sustainable production and consumption system	SDG 12: Ensuring sustainable consumption and production patterns
Forest preservation and GHG reduction	SDG 13: Taking urgent action to combat climate change and its impacts
Forest protection through local populations	SDG 15: Protecting, restoring, and promoting sustainable use of terrestrial ecosystems, sustainably managing forests, combating desertification, halting and reversing land degradation, and halting biodiversity loss
Inclusive and fair model and community-based innovation	SDG 16: Promoting peaceful and inclusive societies for sustainable development, providing access to justice for all, and building effective, accountable, and inclusive institutions at all levels
Grassroots innovation and collaborative governance	SDG 17: Strengthening the means of implementation and revitalizing the global partnership for sustainable development

showcase the initiatives and activities that promote two cases of the CSBE in the Brazilian Amazon, as well as how the community-based grassroots innovation model is structured.

25.4 Case Studies in Sociobioeconomy

This section shows the activities of producing oils from the seeds of *andiroba* (*Carapa guianensis*) and *murumuru* (*Astrocaryum murumuru*) and the sustainable fishing co-management of Pirarucu, which have already been studied within the concept of CE and bioeconomy. Below, through Fig. 25.3, it is possible to

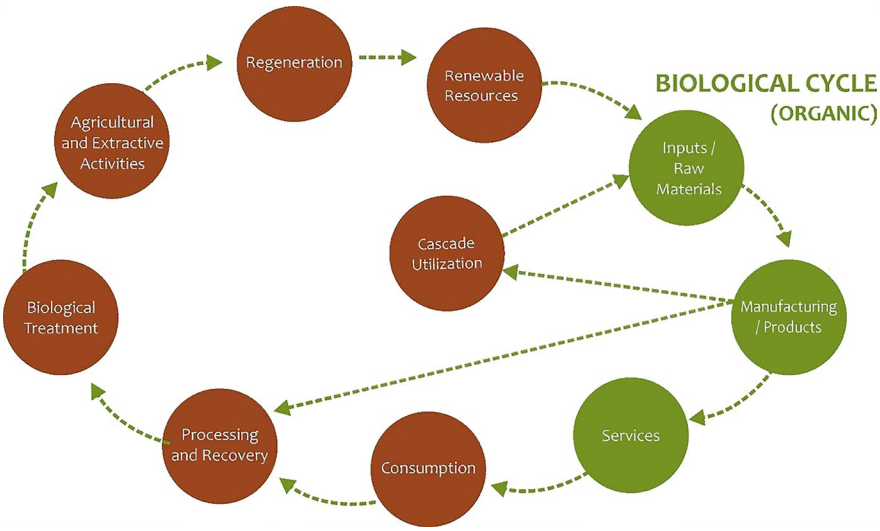

Fig. 25.3 Activities and initiatives that comprise the biological cycle of the Circular Economy (CE) and that have been developed by the value chains of sociobiodiversity products in the Brazilian Amazon

understand how the biological cycle of the CE is embedded in the region and production chains of the bioeconomy under study.

This cycle is characterized, initially, by using inputs and raw materials of biological and renewable origin, followed by the manufacturing of products, provision of necessary services for commercialization (such as marketing, sales, and customer service), and subsequent consumption (by businesses and consumers). In these cases, waste can be reused within the production system itself, as well as through connections with other production chains, where a waste product from one sector can serve as an input/raw material for another value chain.

Cascading reuse is characterized by the direct use of waste/inputs without any form of treatment. A classic example of cascading reuse is the use of gardening or pruning waste to nourish and enrich flower beds and parks through the agricultural technique known as mulching (covering exposed soil with organic matter, such as leaves, twigs, and pieces of wood).

Another fundamental initiative within the biological cycle of the circular economy is processing and recovery. In this process, unlike biological treatment, there is no alteration or transformation of the chemical, physical, and biological characteristics of the materials, even when they are processed for more noble uses. Examples include the development of bioproducts, such as those presented later, made from fish skin and scales, which are processed into high-market potential products (like bags, shoes, clothing, and bio-jewelry). However, the clothing remains made from skin/leather, and the jewelry is made from fish scales.

On the other hand, the treatment of organic waste, which can occur through composting and anaerobic digestion, involves techniques that alter the properties

(chemical, physical, and biological) of the waste, transforming them into other materials/inputs for different purposes/uses. For instance, the input for these systems consists of organic waste (such as food scraps or garden waste), and the outputs/products are composts for agricultural use. Finally, regeneration involves using organic matter to recover soils and degraded areas, which can occur using the compounds produced through treatment techniques, as well as through cascading reuse.

An important observation about Fig. 25.3 is that in the Circular Economy concept, waste must be eliminated from the beginning/conception and considered as resources and by-products. Furthermore, in the Amazon context, organic waste has been reused, either through cascade use or within production chains, as will be demonstrated in the following cases.

Next, an example of CSBE found and analyzed in this study is presented, which can also be applied to other value chains, productive sectors, and territories with similar characteristics. Figure 25.4 illustrates the CSBE activities in the value chain of oil production for cosmetics.

This bioeconomy production system, which demonstrates circularity, begins with the collection activities of *andiroba* and *murumuru* seeds using inputs (baskets and manual collectors) made from natural materials. The seeds then undergo a manufacturing process to produce oil and are sold/commercialized to one of Brazil's leading cosmetic production companies. The collection and processing activities generate waste from the seed husks (which are reused in a cascading manner for direct use in local agricultural and forestry production) as well as the oil sludge (which is repurposed to make soap for local communities). Next, Fig. 25.5 visualizes the value chain of Pirarucu.

The raw materials in this value chain are also of biological origin, including nets, canoes, and wooden paddles, which serve as inputs and equipment for artisanal fishing. The fish are then processed in floating refrigerators, and their meat is marketed and sent to major consumer centers (wholesale and retail, such as distributors,

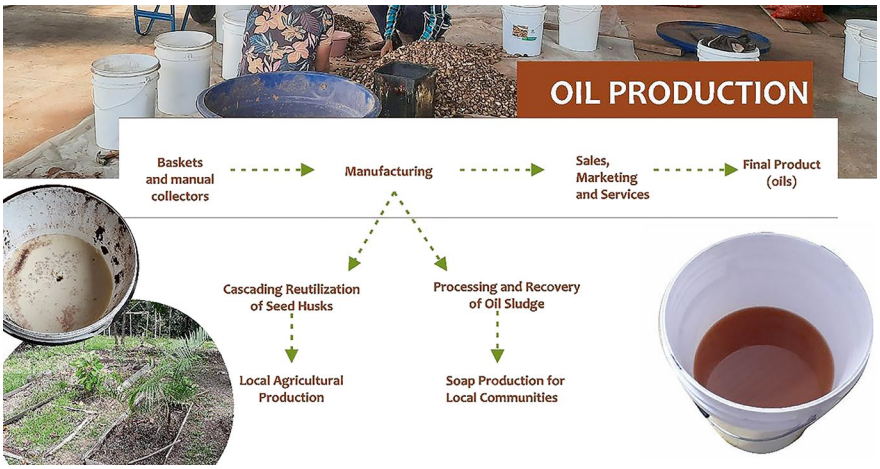

Fig. 25.4 Activities of the CSBE in the seed and oil value chain

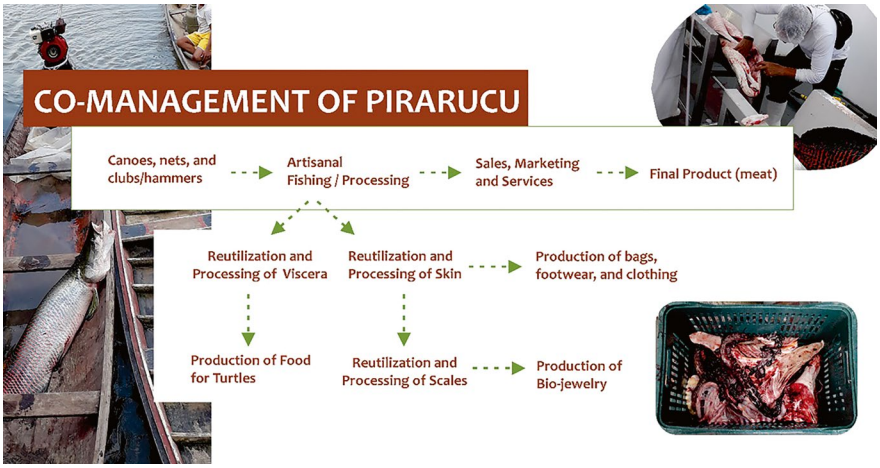

Fig. 25.5 Activities of the CBE in the value chain of Pirarucu co-management

supermarkets, and restaurants in Manaus, Recife, Belo Horizonte, Rio de Janeiro, and São Paulo). During the evisceration process, in addition to the meat, by-products such as the viscera (used for turtle feed), scales (for producing bio-jewelry), and fish skin (for making bags, shoes, and clothing) are also processed and repurposed. Thus, as previously highlighted, it is clear to see the two value chains developing through the concepts of CSBE. The seed collection and processing project involves approximately 400 families, and Pirarucu co-management has been developed by approximately 700 families, contributing to the generation of employment, income, and socioeconomic development of local communities. However, it is important to note that these are still isolated initiatives, as many territories have not yet been able to develop similar value chains. Additionally, other value chains (such as other seeds or other fish) could also draw inspiration from these activities for their development.

The maturity of these chains can be attributed to several factors, with two main ones standing out: the process of territorial management and planning, and the institutions (governments, companies, NGOs, universities, institutes, and local community organizations) and leadership involved in the collaborative governance of these territories and local production chains. Collaborative governance (CG) is a system where the formulation and implementation of public policies must involve people and institutions beyond the state, while always being coordinated by a public agency (be it municipal, state, or federal). These two value chains are integrated within two conservation units (see Fig. 25.6).

The Médio Juruá Extractive Reserve (RESEX) is managed by the Chico Mendes Institute for Biodiversity Conservation (ICMBio), an agency of the Brazilian Federal Ministry of the Environment. Meanwhile, the Uacari Sustainable Development Reserve (RDS) is managed by the State Department of the Environment (SEMA) of the Amazonas State Government. Therefore, both ICMBio and SEMA

Fig. 25.6 General structure of collaborative governance within the two conservation units under study—extractive Reserve (RESEX) of Médio Juruá and Sustainable Development Reserve (RDS) of Uacari—for both systems of Circular Bioeconomy (CBE) (co-management of Pirarucu and production of oils)

are the governmental institutions responsible for all activities occurring within these territories, including the management and sustainable use of natural resources.

In Brazil, the law that regulates and establishes the National System of Conservation Units was enacted relatively recently (in 2000). Thus, many management plans for conservation units have been recently developed and are being implemented. In addition to UCs, Brazil also has specific laws and institutions that regulate the management of Indigenous Lands and the territories and settlements resulting from agrarian reform, which are home to traditional populations such as settlements of afro-descendants (called *Quilombos*) and family farming.

Here, we will present the general structure of governance within two Sustainable Use Conservation Units. Next, Fig. 25.6 will illustrate the governance models that

enabled success and could also serve as examples for other territories with similar characteristics.

Both the collection of seeds and the fishing of Pirarucu are activities that have been carried out for centuries by local traditional communities. However, both the co-management of Pirarucu and the production of oils are also recent activities. The Pirarucu is considered the largest freshwater-scaled fish in the world and was strongly overfished in the last century. However, in 1999, the Mamirauá Institute developed the "social technology for the co-management of Pirarucu," certifying "professional counters," who are the fishermen responsible for counting and certifying the number of fish eligible for fishing (Castello et al., 2009).

This practice spread throughout the Brazilian Amazon, and later the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA) began to regulate, assess, and authorize annual fishing quotas. In this model, IPLCs are legally empowered to protect their fishing grounds against large-scale commercial fisheries. During the dry season, oxbow lakes are discrete units in the landscape and can be monopolized. Adapted to hypoxic environments, arapaima regularly comes to the surface to breathe, which facilitates direct population counts and stock assessments to set sustainable harvest quotas. Protected lakes are guarded by the local dwellers over the entire year. Our previous research shows that protected lakes contain an arapaima population up to 50-fold higher than in unprotected lakes, and over the last 12 years, wild arapaima populations have demonstrated an impressive recovery trend, increasing by 425% (Campos-Silva et al., 2019).

In addition to the conservation outcomes, this model also represents an impressive tool for local development through the gross income for local dwellers, providing opportunities for access to basic consumption items, improvements in housing, and access to health and education needs (Campos-Silva et al., 2021). The arapaima management is also helping with the global fight against gender inequality, providing an unmatched opportunity to include women in decision-making, income generation, and planning the use of natural resources, as the women are for the first time earning their own money from Amazonian fishing (Freitas et al., 2020). The co-management of Pirarucu also contributes substantially to strengthening the social organization of IPLC. Due to its strong social and ecological outcomes and its potential to be replicated, the co-management of giant arapaima has been increasingly recognized as one of the most promising sustainable activities to tackle conservation, food security, and poverty across Amazonia (Campos-Silva & Peres, 2016).

Although the co-management of Pirarucu and the Seed Collection and Oil Production are led and coordinated by local communities and grassroots organizations, other actors are also important for consolidating the activity—as can be seen in Box 25.1.

As mentioned in Box 25.1, there has been recent interest from a large multinational company in purchasing the waste from oil production. In seed collection and oil production activities, there is an important intersection between the public sector, private sector, and community-based organizations, exemplified by the

Box 25.1 Sectors and Institutions Involved in Seed Collection and Oil Production Activities and in Pirarucu Co-management, in the Middle Juruá Region

Government levels and sectors	Co-management of Pirarucu	Seed collection and oil production
Federal Government	ICMBio is involved in territorial management and training local communities (in the case of the RESEX of Médio Juruá), while IBAMA develops regulations and oversees management activities (for both CUs). The federal government can also play a role in purchasing this food, either through the National School Feeding Program (PNAE) or the minimum Price guarantee policy for Sociobiodiversity products (PGPMBio). Recently, as presented in Sect. 25.2, the Federal Government launched new financing modalities, specifically for agroindustries, forests, agroecology, and bioeconomy—through the National Program for strengthening family agriculture (PRONAF)	ICMBio manages the territory and provides training for local communities (in the case of the Médio Juruá RESEX), and can purchase oils through the minimum Price guarantee policy for Sociobiodiversity products (PGPMBio), and funding through the National Program for strengthening family agriculture (PRONAF)
State government	SEMA is responsible for territorial management and training local communities (in the case of the RDS of Uacari)	SEMA is responsible for territorial management and training local communities (in the case of the RDS of Uacari)
Municipal government	Financial subsidy with payment for fuel for transportation and ice for preserving fish, in addition to boat rental	Relevant initiatives were not found
Universities, institutes, and NGOs	These institutions are heavily involved in research and development, as well as in training community leaders and organizations and securing project funding from national and international sources. Examples include improving fish processing techniques, courses on conservation and resource management, developing new processes and products (such as bio-jewelry from scales and bags, shoes, and clothing made from skin), and acquiring machinery and equipment for fish processing	These sectors and institutions work in research and development, as well as in training community leaders and organizations

Government levels and sectors	Co-management of Pirarucu	Seed collection and oil production
Government levels and sectors	*Co-management of Pirarucu*	*Seed collection and oil production*
Private sector	Primarily acts as the consumer market, ranging from slaughterhouses to hotel chains and supermarkets. There are also emerging consumer markets for bioproducts, such as bio-jewelry, bags, shoes, and clothing	In this case, the private sector has been a major driver of innovation in the chain. For a long time, there was only one customer/consumer market (a large national company), which not only consumed the oils but also invested in building agroindustries and training human resources for the development of bioproducts (from andiroba and murumuru). Recently, another large multinational company has also begun investing in the oil chain of Médio Juruá by providing financial management courses and starting to purchase waste from oil production, such as cakes and pomaces
Community-based organizations	These institutions form the backbone of this chain and are organized both for production and for marketing products, playing a significant role in product development and the entire value chain	Similar to the case of Pirarucu, these institutions are well-organized for both the production and marketing of the products. It is through this traditional knowledge that the practices of cascading reuse of seed husks (for local gardens) and the waste (oil sludge) from oil production (for soap production for local communities) have been implemented

creation of the "Médio Juruá Fund," managed by a governmental institution, a company, and three community-based organizations, with the aim of financing and developing socioenvironmental projects that are community-focused, organizational, productive, and that seek sustainable development in the region (including the seeds and oil production chain). However, these activities still lack a better understanding of the real socioeconomic impact on communities, such as jobs and income generation.

Another relevant issue in the action of communities is that, in addition to the structure of production and commercialization, due to the absence of certain services and public policies, the grassroots organizations themselves have been organizing to promote initiatives in logistics, transportation, communication, sanitation, as well as financial subsidies.

Thus, two other very important aspects for the development of productive sectors and value chains are financing initiatives and infrastructure (considered support activities within the value chain literature). These are specific aspects for the region and are still considered important gaps to be filled, both in the development of essential infrastructure and public services (such as logistics and mobility; communication; health; energy; sanitation; waste management; and housing), as well as in specific credit lines for financing these sociobiodiversity value chains.

In terms of infrastructure, all three levels of government (municipal, state, and federal) bear responsibilities and legal assignments for the development of these sectors and policies in the region. As for financing, there are currently federal government credit lines, such as the National Program for Strengthening Family Agriculture (PRONAF), in addition to resources raised by third-sector organizations (such as NGOs and Institutes) from international agencies and institutions. However, regarding financing, a key challenge remains: making these resources more accessible, frequent, and scalable for communities, without relying solely on "donor or philanthropic" institutions.

25.5 Challenges and Opportunities for Circular Sociobioeconomy in the Brazilian Amazon

In light of global predatory models (of linear economies dependent on fossil and non-renewable natural resources) and those specific to the Amazon region (such as timber, cattle, and mining), the Circular Sociobioeconomy presents itself as an important and fundamental alternative for promoting biodiversity conservation, combined with socioeconomic development and the preservation of cultural practices of local traditional communities, which are essential for the functioning of a circular bioeconomy.

The Amazon is vast in territory and social, cultural, and environmental diversity, has great potential for expanding these activities, and still harbors many little-known riches (such as pharmaceutical benefits and various other biodiversity products). The potential of the bioeconomy remains largely unknown and underdeveloped, representing an immense field to be explored. However, strengthening local communities, who are the managing agents for keeping the forest standing with their social and cultural practices, is crucial for operationalizing the CSBE. Even though cultural practices are context-specific and may not universally contribute to sustainability, many cultural aspects, such as traditional

Collaborative Governance
Another important aspect of this work is understanding the significance of the various drivers and enablers of actions and public policies (within the context of collaborative governance) for the development of these productive chains. A co-production of public policies among various state organizations and communities is crucial for strengthening the agents that generate the CSBE and maintain the sustainability of ecosystems. The synchronization of a puzzle (encompassing multi-level and multi-sector/multi-actor perspectives) of organizations and institutions presents both a challenge and an opportunity for this vast and diverse region, without losing sight of the importance of governmental institutions in coordinating and controlling initiatives and collaborative governance processes. The state (whether municipalities, states, or federal government) has the mission of safeguarding public and collective interests, which must always take precedence over individual interests.

Global–Local Connection
Within the multi-level perspective, it is necessary to understand the international/global influences that permeate all other levels, from regional and national to state and local (municipal levels). Here, the reverse exercise is also important; for instance, understanding how local initiatives can contribute to global goals (such as the SDGs) and GHG reduction targets). Furthermore, the multi-sectoral and multi-actor vision should clarify how each institution (public, private, or third sector) can contribute to the development of a specific territory and its local productive chains.

Strengthening Local Organizations
In this study, it can be observed that sustainable use conservation units, when supported by the social participation of strong local actors and institutions, can be significant drivers of biodiversity conservation and the generation of local jobs and income. This study also highlights the importance of capable local institutions (such as resident and producer associations) as protagonists in base innovation systems—both in the co-management of Pirarucu and in the processes of seed collection and processing. Research organizations and third-sector projects (such as universities, institutes, and NGOs) have also been crucial for the development and improvement of local productive chains, engaging in both research and development as well as resource mobilization, training, and serving as an important voice for the world through the motto "conservation of nature through local communities and traditional knowledge." Partner companies that are genuinely committed to local sustainable development can also play a vital role in promoting the CSBE in the region, as demonstrated by the consumer market for the two value chains.

Investments in Infrastructure and Financing

Regarding the circularity and development of these sociobiodiversity product chains, it is important to highlight that the processes of manufacturing, processing, and reutilization are possible due to the infrastructure of the local agroindustry. The agroindustry for producing oils from seeds was financed by a national bank, a multinational beverage producer, the government of the state of Amazonas, and an organization from the third sector. Similarly, the value chain of Pirarucu, which also requires floating boats for evisceration and processing facilities, has also received financial support from various public, private, and third-sector institutions.

In this way, the importance and need for financial support for investment in technology, infrastructure, and local capacity building are understood, so that manufacturing, processing, and reutilization activities can occur, generating a growing local value addition for the continuous increase of community income. In other locations that lack this support, initiatives can still be considered rudimentary and incipient, with no gain in scale (production volume) and scope (variety of products within the same value chain).

The Middle Juruá Region has been considered an important location for the development of projects that combine environmental conservation with local socioeconomic development (Campos-Silva et al., 2020). However, although promising, these initiatives depend on initial external support, due to the lack of resources and local capacity to initiate or enhance these activities. Therefore, even with the success of local initiatives, some learnings and results will be presented here about the existence of an urgent demand for investments in logistics and infrastructure, access to credit/public financing, and training of local communities in the Amazon, to provide alternatives for sustainable livelihoods for the local population. Investments in infrastructure, for the value chains studied here, also include refrigerated boats, equipment for processing native fruits, and warehouses for storing and marketing products. Regional infrastructure and logistics initiatives should follow sustainability standards and minimize local impact (i.e., Paes et al., 2020), prioritizing investments in basic sanitation, drinking water, waste management, solar energy, health and education facilities, as well as mobility and transportation by boat.

knowledge or social capital from the traditional way of community organizing, can support the implementation of circular bioeconomy initiatives. Therefore, by understanding the concepts and practical structures of the CSBE, models like this could be replicated in other value chains that have been on the rise in recent years.

25.6 Conclusions and Future Directions

This study aimed to present concepts of the Circular Sociobioeconomy and demonstrate how innovative management initiatives for products and value chains of sociobiodiversity are taking place in the Brazilian Amazon. It is possible to understand that the concepts of the CSBE are still in development and that the narratives and practices of the CE are more complementary and aligned, while the different practices and visions of the bioeconomy often appear as antagonistic and even conflicting.

However, this study focused on the biological cycle of the CE and the theory of Ecological Bioeconomy, where sustainability indicators take precedence over the need for unilateral economic growth. Additionally, it incorporated the concept of sociobiodiversity products and sociobioeconomics, which are managed by traditional local communities. Thus, this study presented a model of CSBE that: (1) considers local traditional populations and communities as protagonists in the processes and management of value chains; (2) generates local socioeconomic development through employment, income, and profit for local institutions; (3) contributes to keeping the forest standing through the sustainable management of biodiversity; and (4) contributes to the SDGs and helps mitigate climate change.

Even though promising, this model still requires local improvements, such as simplified and accessible financing and better infrastructure (both for production systems and public services like transportation by boat, health, energy, sanitation, and waste management). For the expansion of this model to other regions and value chains in the Amazon, specific project funding is necessary to promote investment in research and innovation, technology, infrastructure, and the capacity building of local communities and institutions. That is, a financing model for intensive agriculture (such as monoculture and livestock) cannot be replicated in this context. There are important government initiatives, such as those demonstrated by federal government programs (e.g., PRONAF and PGPMBio); however, to leverage these value chains of sociobiodiversity products in other territories and products, there must be specific and targeted projects and funding for these realities.

The structure of collaborative governance also proved to be fundamental in promoting local sustainability through the alignment of governments, the private sector, research institutions, and local communities. To this end, a deeper understanding of how the organizational capacities of institutions are being built and how innovation processes are occurring presents important research gaps that need to be addressed, to expand these initiatives to other locations. Another important aspect of

CG that can be developed is the study of other regions and management modalities (such as Indigenous Lands and Agroextractive Settlement Projects—PAEs) to understand the organizational and governmental dynamics in different territorial realities that also face management challenges, similar to conservation units. Furthermore, to promote CSBE in the Amazon, there is an urgent need for more projects and studies on other value chains of sociobiodiversity, as well as quantitative data on the input and output flows of these chains—specifically, how much they are producing, and which waste and inputs can be reused within their production systems or in other value chains.

There is no single solution to guarantee a sustainable future for the Amazon, but the overall key to doing so certainly lies in how to integrate the conservation of biodiversity, urbanization, and infrastructure, and the development of local communities. CSBE concepts are important for designing and operationalize solutions.

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Chapter 26
Promoting Circular Economy in an Argentinean Producers' Network

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26.1 Why Adopt the Circular Economy in the Argentinean Agribusiness Sector?

Agribusiness chains are currently facing several challenges, both systematic and specific to the activity. Firstly, the expected increase in world population, from 8 billion by the end of 2020 to nearly 10 billion in 2050 (UN, 2020), is the main driver of a growing demand for food, fibers, and energy, both in quantity and quality (Van Dijk et al., 2021). Secondly, this sustained demand requires an increase in production that must be achieved with a necessarily lower negative impact on the environment. Thus, today the focus is on adopting process technologies and knowledge to improve productivity while reducing environmental impact is needed (Andrade, 2020). These demands occur at the same time as a greater recurrence of extreme weather events (climate change) in a more interconnected, interdependent, and unstable world (FAO, 2021), which means that production, processing, and marketing take place in more volatile contexts. Therefore, another clear challenge for agricultural activities is to manage more and different sources of risk linked to

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production, such as climate and health, markets (input and output prices), institutional, personal, and financial (Hardaker et al., 2004).

Most of the efforts aimed at solving the new challenges and laying the foundations for developing sustainable agriculture have been insufficient, making it necessary to explore integrated approaches. In turn, the current economic model based on the "extract-produce-waste" paradigm is being widely criticized for its low sustainability (EMF, 2015). In this context, circular economy models in agribusiness activities are beginning to emerge to promote the sustainable development of the sector and, therefore, of the country. These models are emerging worldwide, particularly in smaller-scale agricultural systems that are supported by encouraging policies (Esposito et al., 2020). In this context, the question arises as to whether these circular economy models can be adapted to Argentine production systems, which are medium to large in terms of surface area, are highly variable in terms of diversification, and have few government policies to promote them.

The circular economy is defined as one in which the value of products, materials, and resources is retained in the economy for as long as possible and waste generation is minimized (European Commission, 2015). This definition seeks the benefits of adopting circular economy models in the face of new challenges: less use/consumption of resources/inputs, less waste generation and environmental impact, new jobs and investments, and innovation and networking. However, to implement these models it is crucial to overcome important barriers such as specific policies and regulations, lack of incentives and financial capacity, lack of technology and innovation, lack of supply chain design and optimization, and lack of economic benefits and high investment costs, among others (Gedam et al., 2021; Van Hoof et al., 2023). In the case of financial barriers, the gap between what is offered and what is required to meet Sustainable Development Goals (UN, 2024) is a key issue to consider in initiatives with sustainable approaches. Likewise, technology and innovation, although data and information exist in various sectors and based on agribusiness cases, are applied in other development systems and policies.

This chapter presents the main lessons learned from a joint initiative between CREA (Regional Consortium of Agricultural Experimentation) and the Embassy of the Kingdom of the Netherlands in Argentina, which seeks to provide answers to the challenges of the Argentine agribusiness activity through circular economy models. It was planned in sequential stages to cover from concept to application in Argentine cases. Based on the joint and collaborative learning of the CREA network (Box A), this work seeks to put the circular economy concept on the agenda and to understand, through the analysis of cases, the value for agricultural companies to start working on this issue, identifying benefits and future opportunities.

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Box A What Is CREA?

CREA Argentina is a non-profit civil association integrated, conducted, and financed by producers, who join a network with more than 60 years of experience in sharing knowledge and experiences in a collaborative work. CREA reunites nearly 2200 producers distributed geographically across the country, who work monthly in ~240 groups of 8–12 following a particular methodology to share knowledge and find collaborative solutions to common problems. It is a joint learning process from peers' experiences, assisted by a technical advisor. The institution has a national scope and is deeply rooted into the Argentinean territory, embracing different agroecological regions, and diverse productive systems. Currently, CREA groups of producers are gathered in 19 regions according to the geographical area. Likewise, the institution stands out for the development of topics related to the sector; one of its goals is the generation and transfer of knowledge, collaborating with its development. CREA companies, which are integrated into the community, are a reference for innovation and work for the sustainable development of their own companies, the localities they belong to and the country.

The CREA methodology has been transferred to neighboring countries such as Uruguay, Bolivia, and Paraguay, where producer associations have been formed. This form of collaborative learning has even reached a European country such as Georgia.

The initiative was based on four drivers:

1. CREA culture. CREA is a technical entity in which sustainable development in general, and sustainable agricultural production in particular, occupy a priority space in its agenda. In this sense, CREA understands sustainable agricultural production as "a way of carrying out production aimed at meeting the needs of present generations without compromising the possibility of future generations to meet theirs, considering economic, social, and environmental aspects of production and seeking to maintain a balance between them" (Vázquez Amábile et al., 2018).
2. Current processes of transformation of agriculture. We recognize and work on at least three major processes. Firstly, it is necessary to guarantee a production that is careful with health and the environment, providing security to society, and at the same time designing systems that are more resilient to environmental changes. Secondly, the development and adoption of new digital technologies will change the pace. Finally, we must consider production and marketing strategies that allow us to reach increasingly segmented markets with different products, or products produced in a different way.
3. Demand and needs of the CREA network. As a first step in mapping circular economy initiatives in the CREA network, questions were asked in the

July 2021 SEA[1] survey, in which 1148 CREA producers (~62% of the network) and 199 CREA technical advisors (~95% of the network) participated. 78% of CREA producers said they knew little or nothing about circular economy, while 4% indicated that they were applying the concept, and another 4% planned to apply it in the short or long term. In the case of advisors, 61% said they knew little or nothing about the topic, and 7% were already applying it in their groups. The subgroup of producers or advisors who knew little or nothing about the concept of circular economy, in addition to those who indicated that they knew about it but were not applying it, were asked if they were interested in learning more about the topic. Here, eight out of ten producers and nine out of ten technical advisors responded that they were interested. These results support the CREA network's initial interest in addressing circular economy models and highlight the need to learn about the subject. To conclude, the analysis of CREA cases that are already adopting circular economy concepts is important.

4. Interest of the Netherlands in the circular economy. It is one of the world's leading countries in the agricultural sector, highlighting its technological innovation (MANFQ, 2018). In this aspect, Wageningen University & Research (WUR) plays a central role, being recognized worldwide for its agricultural research.

The following sections describe the sequential stages of the initiative: (i) a literature review and exchanges with key stakeholders to establish a locally adapted definition of circular economy; (ii) the characterization of CREA cases that are implementing circular economy in agribusiness to understand the current situation and identify drivers and barriers to adoption; and (iii) the suggestion of possible tools to evaluate and improve the adoption of circular economy in Argentine agribusiness.

26.2 What Definition of Circular Economy Is Suitable for Argentinean Agribusiness?

As a first stage of the initiative, during the second half of 2021, a "conceptual debate on circular economy" was carried out through a literature review and exchanges with different experts on the subject, such as researchers from national and foreign institutions, government technicians, and producers and consultants who were applying the concept. The debate focused on defining a concept of circular economy applied to the Argentine agribusiness sector that would not only serve to guide the analysis but also answer questions such as: What are we talking about when we refer to this term? What is the definition of circular economy that best suits Argentine agricultural systems?

[1] CREA's Agricultural Survey System (SEA CREA) is a four-monthly survey of CREA producers and technical advisors that inquiries about the perception and expectations regarding production, economic, financial and business matters, among others.

The literature review provided us with elements for discussion in a series of meetings and workshops designed for this purpose. This made it possible to agree on the following definition: *"The circular economy in agribusiness seeks to reduce, reuse and/or recycle materials, components, or products in both biological and technical cycles, to promote sustainable agribusiness developments to preserve natural capital and optimize the use of resources. In this way, the circular economy in agribusiness increases the resilience of the ecosystem for the continuous creation of regional value."*

26.3 How Is the Circular Economy Being Applied in the CREA Network?

The second stage of the initiative was the characterization of CREA cases that were adopting the circular economy in agribusiness. It was based on a descriptive study that involved, after a literature review that allowed us to define it, a new survey using the SEA one. The survey included questions developed to identify success cases and opportunities for adoption based on the work of Donner et al. (2021). On this occasion, the analysis also included other data collected by the CREA Information System. Thus, the survey responses were cross-referenced with the data obtained from the CREA Census,[2] the last edition of which was carried out in 2019.

26.3.1 Level of Adoption of the Circular Economy in the CREA Network

A total of 1173 CREA producers responded to the March 2023 SEA survey. Of these, 22% (294 cases) had already implemented circular economy models in agribusiness, while 51% had not yet adopted them but planned to do so. The remaining 27% were not interested in the circular economy and did not plan to venture into it in the future. In all CREA regions, there were producers who responded that they were carrying out the circular economy. Grouped in macro regions, the cases of the circular economy were distributed as follows: 49% in the center-east (Pampas), 17% in the northwest, 16% in the northeast, 13% in the center-west (Cuyo), while the south of the country (Patagonia) had only 5% of the cases. These percentages are in line with the distribution of CREA producers (both those who make circular economy and those who do not), with some regional differences: In Cuyo and Patagonia, the proportion of total CREA producers is lower than that of circular

[2] The CREA Census is a layer of the CREA Information System that collects data and structural information on CREA members. The initiative is carried out every 5 years, with the last edition in 2019.

economy cases surveyed (5% vs. 13% in Cuyo, and 2.5% vs. 5% in Patagonia); while in Pampas, the opposite occurs (61% of total producers vs. 49% of circular economy cases).

Analyzing the main productive activities, it was identified that in the most intensive livestock activities the proportion of cases of producers applying circular economy concepts was higher. 68% and 41% of pig and dairy producers, respectively, reported having circular economy initiatives. Sheep production showed a similar level of adoption of a circular economy as dairy farming, with 38% of the producers surveyed applying these production models, but most of them were cases of renewable energy production (wind or solar energy) to reduce energy inputs in their farms. In the case of the most frequent extensive activities in CREA, such as livestock and annual cash crops, the level of adoption was lower in percentage terms, with 20% and 19% of the producers surveyed, respectively. The main circular economy initiatives implemented by CREA producers[3] were the use of effluents as fertilizers (144 cases) and the generation of renewable energies (125 cases). To a lesser extent, there were cases of biogas generation (17), generation of biomaterials, bioproducts, and/or bioinputs (23), and other initiatives (27). Figure 26.1 groups these circular economy initiatives in the mentioned macro regions. Among the most adopted initiatives, the use of effluents as fertilizers was very important in the Pampas and Northwest, while renewable energy generation was very important in Patagonia.

26.3.2 Drivers of Circular Economy Adoption in the CREA Network

Obtained answers were used to describe the level of knowledge, barriers, and impacts of adoption of circular economy in agribusiness, among other issues. The main findings are described below.

Both the economic and environmental dimensions were relevant when producers decided to implement circular economy initiatives in the CREA network. Among drivers, 54% of producers mentioned the reduction of environmental impact, followed by factors that can be included in the economic dimension, such as increased production (44%), cost reduction (39%), and value addition (29%). When producers were asked about the impact of those initiatives, 3 out of 4 producers reported knowing the impact of their activities. More than half of the respondents consider that applying circular economy models has a positive impact on the quality of soil, water, air, and biodiversity conservation. The positive impact on people's well-being and public opinion was also highly valued (>70%). Although only 40% of respondents consider the circular economy to be positive for local economic

[3] Some of the CREA producers who responded that they are implementing a circular economy indicated that they are applying more than one initiative.

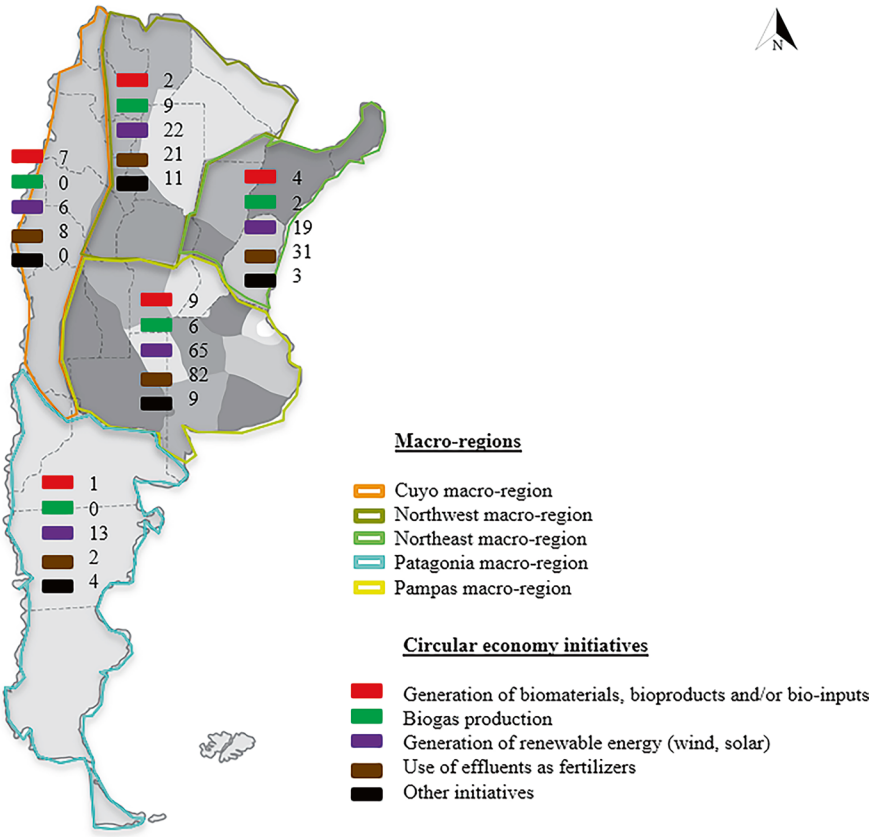

Fig. 26.1 Circular economy initiatives in the CREA network, distributed by macro-region. Within each macro-region, the CREA regions are indicated. Circular economy initiatives are grouped as: use of effluents such as fertilizers, generation of renewable energies, generation of biogas, generation of biomaterials, bioproducts and/or bioinputs, and other initiatives

development, 70% expect the economic impact of adoption to be positive, and 50% expect this improvement to occur in the medium to long term. Certainly, for the impact to be transferred beyond the confines of the farms, it will be necessary to overcome some barriers linked to public policies and regulations.

The circular economy in agribusiness is also seen as an approach capable of providing tools to better manage the different sources of risk. In this regard, 40% of those surveyed considered that the circular economy helped them to adapt, in the short or medium term, to different adverse events. Of the remainder, half indicated that their capacity to adapt remained the same and the other half did not yet know. On the other hand, the obstacles to adoption reported by producers were related to both exogenous and endogenous issues. The high level of investment required and the lack of financing to implement initiatives were highlighted (50%), as well as insufficient training or lack of time on the part of potential adopters (48%). Few producers perceived resistance to change as an obstacle (10%).

Starting in 2010, the pace of adoption of circular economy initiatives in CREA accelerated. Among the respondents, the first two cases of circular economy in agribusiness are from 1995. From then on, there was a period of about 15 years in which a little more than 2 producers per year started working in the circular economy. Since 2010 the average rate was almost 15 producers per year starting circular economy activities, with a clear acceleration showing a peak in 2020 where 30 cases were registered. Although no specific drivers were identified, the increased adoption of circular economy initiatives may be quite like the increased presence and demands of environmental issues in the productive agenda, from the enactment of the General Environmental Law in Argentina to the proclamation of the 2030 Agenda at the international level. In the same sense, an important fact to highlight is that in 2010 CREA's Environmental Area was created, so this institutional action could have had some impact on the communication of certain issues and subsequent decision making of the network's producers.

26.3.3 Profiles of CREA Cases Adopting Circular Economy

When crossing data from the SEA survey and the CREA census, data were discarded because the SEA survey allows anonymous answers (the producer cannot be identified), and some cases were not part of CREA at the time of the Census (2019). Thus, as a result, 590 of the 1173 respondents could have their profile supplemented with CREA Census data. These cases are sufficient to provide valuable information to complement the characterization of the implementation of circular economy processes and models in the CREA network.

The level of adoption of circular economy initiatives was affected by the level of education, with no influence of age or gender. Adoption was significantly higher when the producer had postgraduate education, where 30% were doing circular economy in agribusiness. There was practically no difference in the level of adoption among producers with secondary, tertiary, or university education. Approximately one fifth of them were applying circular economy models in their systems. Except for producers over 60 years old, for whom the level of adoption of the circular economy was 6%, in the other age ranges (under 40 years old, between 40 and 50 years old, or between 50 and 60 years old), approximately one fifth of the producers applied circular economy models. Similarly, women (23%) had a slightly higher adoption rate than men (21%), which also had no significant effect.

Environmental issues had an impact on the incorporation of circular economy in agribusiness in the CREA network. Almost half of the producers (46%) who had demonstrations or social claims adopted circular economy models, while a fifth did not have any type of conflict. In fact, the impact of social protest seems to have been even greater than that of legal channels, since only 26% of those who suffered administrative claims or complaints indicated that they were doing circular economy in agribusiness. The professionalization and advice available to the producer tended to explain these responses. Those agricultural companies that had a more

professionalized[4] management showed a higher adoption rate (27% vs. 20% for the rest). In this sense, agricultural companies with advice showed a higher level of adoption of the circular economy than those without advice. Although both types of advice showed a positive impact on the adoption rate, it was more relevant in environmental issues (38% vs. 19%) than technological (26% vs. 19% of producers without advice).

26.4 How Could the Circular Economy Be Promoted in Argentine Agribusiness?

The third stage of the initiative focused on possible tools to evaluate and enhance the adoption of the circular economy in agribusiness. In this sense, a set of specific indicators was developed to characterize and measure the impact of the incorporation of circular economy models in agribusiness systems in Argentina and a proposal for a financial instrument to promote sustainable finances through the circular economy in agribusiness was generated.

26.4.1 Promoting Specific Knowledge

To promote specific knowledge, a set of indicators to evaluate cases of circular economy in agribusiness was defined based on indicators already developed and compiled by CREA's Environment, Economics, and Business Areas. They were selected based on the following criteria on the design, construction, and interpretation of indicators:

(i) It is directly associated with a key aspect in terms of sustainability.
(ii) It is based on established definitions and measurements in the literature.
(iii) Its scope is broad, being flexible across different contexts.
(iv) The indicators were tested and validated to measure circular economy cases with reliable data.
(v) Its results are easy to interpret, with a meaning useful and applicable.
(vi) It can be used for regular monitoring.

These considerations allowed the selection of 13 indicators that are grouped according to the sustainability dimension on which they focus within the circularity analysis (Table 26.1). The environmental dimension deals with operations related to circularity within the different environmental compartments and with the

[4] A company is considered to have a professionalized management if it periodically holds shareholders' meetings, managers' meetings, and board of directors' meetings.

Table 26.1 Set of indicators defined to evaluate cases of circular economy in Agribusiness. The category, subject group, and unit of measurement of each is indicated

ID	Category	Thematic group	Indicator	Unit
1	Environment	Waste	Waste valorization rate	%
2	Environment	Inputs	Inputs circularity rate	%
3	Environment	Nutrients	Nutrient balance and circularity	kg/ha, %
4	Environment	Energy	Energy circularity	t/kWh, %
5	Environment	Air	Greenhouse gas emissions	tCO2 eq/ha
6	Environment	Water	Water circularity	%
7	Social	Collaboration	Circular synergies	%
8	Social	Communication	Circular communication	Number
9	Social	Regulation	Compliance with good agricultural practices	%
10	Social	Labor and human capital	Circular employability	%
11	Economy	Business management	Earnings before interest taxes depreciation and amortization	USD/current ARS
12	Economy	Business management	Circular contribution margin	USD/current ARS
13	Economy	Infrastructure and technology	Circular economy in agribusiness technical cycle	%

materials used throughout the production chain; the social dimension contemplates the actions and perceptions of the agricultural company with respect to its relations with the community, suppliers, and external entities. Finally, the economic dimension focuses on the company's efforts on maximizing profits, considering the circularity of the system. In turn, the indicators were separated according to the thematic group of relevance, trying to cover as many factors involved in the system as possible.

The specific set of indicators is in a developmental phase, emphasizing the experimental and evolving nature of measuring circular economy practices. While no universally recognized indicator exists, the indicators proposed aim to characterize circularity at the farm level, enabling both individualized analysis and comparative benchmarking across CREA producers. This approach allows for actionable insights into current practices, future priorities, and the potential to scale these methodologies to a regional level.

26.4.2 Promotion of Sustainable Finance

The financial gap between what is offered and what is required to comply with the 2030 Agenda is a fundamental issue to consider in initiatives with sustainable approaches. In this sense, we worked on the promotion of a sustainable finance tool to channel capital and to provide an institutional framework for companies

developing models of circular economy in agribusiness in Argentina. The following are two sustainable finance options linked to the circular economy for the local Argentine market:

(i) Social, Green, and Sustainable Bonds (SGSBs), for specific use of funds (Sanz-Paris & Peláez, 2021).
(ii) Sustainability-Linked Bonds (SLBs), for general use of funds with a sustainable approach (Pfaff et al., 2024).

There is no specific definition of SGSBs, but ICMA has established principles that allow standardizing the market, providing the general framework that covers its procedures, eligibility criteria, operations, and management itself. Meanwhile, SLBs have been created by ICMA and are defined as those bonds for which the financial and/or structural characteristics can vary depending on whether the issuer achieves predefined sustainability objectives. Issuers are thereby committing explicitly (including in the bond documentation) to future improvements in sustainability outcome(s) within a predefined timeline. Those objectives are measured through predefined Key Performance Indicators (KPIs) and assessed against predefined Sustainability Performance Targets (SPTs). A key point is that the funds are obtained for general corporate purposes; therefore, the specific use is not decisive for their categorization.

Although there are proposals for indicators available, among which those presented in Argentina's Sustainable Financing Framework (MEA, 2023) stand out, for the case of processes, businesses, or activities that are based on circular economy in agribusiness, it is proposed to consider some of the indicators that make up the set presented above (Table 26.1): Waste Valorization Rate (%), Inputs Circularity Rate (%), Nutrient Balance and Circularity (kg/ha or %), Energy Circularity (t/kWh or %), Greenhouse Gas Emissions (tCO2 eq/ha), Water Circularity (%), Circular Synergies (%), Circular Communication (Number), Compliance with Good Agricultural Practices (%), Circular Employability (%), Earnings Before Interest, Taxes, Depreciation, and Amortization (USD), Circular Contribution Margin (USD), and the Circular economy in agribusiness Technical Cycle (%).

This set of indicators was developed with the purpose of monitoring and diagnosing specifically the impact of the circular economy models in the different dimensions of sustainability. Thus, these indicators can be used for the SGSBs approach (qualitative-quantitative indicators) as well as for the SLBs (KPIs and SPTs).

In the case of SPTs, reference values cannot be defined universally; they must be defined on a case-by-case basis. However, they must meet the following criteria:

– Represent a material improvement in the respective KPIs.,
– Where possible, be compared to an external index or benchmark.
– Be consistent with the overall sustainability strategy.
– Be defined with reference to an established period or date.

26.5 Conclusion and Future Directions

The activities or processes of application of circular economy in agribusiness within the CREA producers' network have increased during the last decade, showing a growing willingness to implement sustainable practices on the part of entrepreneurs. However, there are significant challenges in financial management and training of the different members of the company on the subject. Although the acceleration in the adoption of circular economy models has possibly been driven by local, national, and/or global environmental events and regulations, as well as by institutional actions of the producer network, circular economy initiatives in agribusiness are not exempt from problems or situations that act as barriers to entry, where financial and capacity issues are the most important. Although, in general, the circular economy is valued for its positive impact on the environment and the capacity to manage adverse events, there are other relevant factors that facilitate its adoption, such as the level of training of the decision-maker, the professionalization of the company's management, and both environmental and technological advice.

The choice of circular economy models that adapt to each production system in Argentina requires continuous learning. The number and variety of cases of producers and regions in which the circular economy is already being applied in agribusiness represent a valuable source of information for other producers who want to get started. The CREA methodology of exchange of experiences and learning among colleagues can enhance and accelerate the adoption process. In this sense, it is necessary to have processes and tools that allow comparisons between different systems and to analyze their evolution. The set of indicators presented in this chapter may be useful for this purpose. However, it needs to be tested and validated in different cases of application.

Circular economy models require both a favorable macroeconomic context and adequate financial strategies. Argentine agricultural entrepreneurs work mostly in a context of high political and economic volatility, where they must establish medium-to-long-term investments, such as circular economy initiatives in agribusiness. Establishing and maintaining clear institutional rules that encourage the adoption of more sustainable and resilient production systems, such as the application of some circular economy models adapted to local conditions, requires consensus between the public and private sectors. At the same time, sustainable financing strategies, such as those described in this chapter, should be promoted to support the adoption of the circular economy in agribusiness.

Appendix

Set of 13 indicators defined to evaluate cases of Circular economy in Agroindustry. A brief description, the calculation method and the practical interpretation of each one of them is presented. The indicators are grouped in the three dimensions of sustainability: environmental, social and economic.

Environmental Dimension.

1. *Waste Valorization Rate*

Description: This indicator measures the percentage of waste generated at the agribusiness establishment that is valorized and reintroduced into the production system. By prioritizing waste revaluation, such as recycling of materials or conversion of organic waste into energy, the facility reduces its dependence on landfills and minimizes its environmental impact.

Calculation: Ratio of revalued waste to total waste generated, expressed as a percentage.

Interpretation: Higher indexes indicate better waste management practices and greater circularity within the production system, contributing to resource efficiency and carbon footprint reduction.

2. *Inputs Circularity Rate*

Description: This indicator assesses the proportion of secondary inputs (materials derived from recycled or renewable sources) used in production processes compared to total inputs. It emphasizes the substitution of virgin materials with more sustainable alternatives.

Calculation: The ratio of secondary inputs to total inputs, expressed as a percentage.

Interpretation: A higher percentage reflects a greater integration of circular materials in production, which reduces dependence on non-renewable resources and improves the sustainability profile of the facility.

3. *Nutrient Balance and Circularity*

Description: This dual-purpose indicator evaluates both the nutrient balance (inputs versus outputs) and the percentage of nutrients recycled within the system. The nutrient balance ensures that over- or under-use of nutrients is avoided, while the circularity component measures the efficiency of nutrient recovery and reuse.

Calculation: The nutrient input-output balance is calculated from inputs such as fertilizer and outputs such as crop yield. Circularity is determined by the percentage of recovered nutrients that are reintroduced into production.

Interpretation: Supports precision nutrient management, reducing environmental losses while maintaining soil fertility.

4. *Energy Circularity*

Description: This indicator encompasses two key aspects: energy efficiency (the effectiveness with which energy inputs are converted into production outputs) and the proportion of renewable energy sources used in operations.

Calculation: Efficiency is calculated as the ratio of production output to total energy consumption. The share of renewable energy is derived from the proportion of energy generated from renewable sources.

Interpretation: Promotes the transition to low-carbon energy systems, reducing greenhouse gas emissions and operating costs.

5. *Greenhouse Gas Emissions*

Description: This indicator measures total greenhouse gas emissions (expressed in CO2 equivalent) per hectare, encompassing emissions from direct agricultural activities and associated processes.

Calculation: Emissions are calculated using IPCC methodologies, incorporating factors such as fuel use, fertilizer application and livestock management.

Interpretation: Provides a baseline for assessing and implementing mitigation strategies, consistent with climate action objectives.

6. *Water Circularity*

Description: Water Circularity evaluates the efficiency of water use within the facility by measuring the proportion of water recovered, reused and conserved in production processes.

Calculation: The sum of reclaimed and reused water divided by total water used, expressed as a percentage.

Interpretation: Highlights sustainable water management practices, reducing dependence on external water sources and addressing the challenges of water scarcity.

Social Dimension.

7. *Circular Synergies*

Description: This indicator assesses the facility's collaboration with suppliers to implement Circular economy practices, such as using sustainable inputs or sharing by-products within the supply chain.

Calculation: The percentage of suppliers participating in Circular economy initiatives relative to the total number of suppliers.

Interpretation: Promotes shared responsibility and innovation throughout the supply chain, improving overall sustainability.

8. *Circular Communication*

Description: This indicator measures the number of initiatives (such as workshops, training sessions and public campaigns) aimed at raising awareness and educating stakeholders on CE practices.

Calculation: The total number of communication and training activities conducted in a given period.

Interpretation: Reinforces stakeholder engagement and knowledge dissemination, fostering a culture of sustainability.

9. *Compliance with Good Agricultural Practices*

This indicator monitors compliance with established environmental, social and operational best practices.

Calculation: The percentage of applicable best practices implemented by the facility.

Interpretation: Ensures regulatory compliance and promotes responsible management practices, reducing risks and improving sustainability performance.

10. *Circular Employability*

Description This indicator reflects the percentage of jobs directly or indirectly related to Circular economy activities within the facility, emphasizing the socioeconomic benefits of the Circular economy.

Calculation: The number of employees related to the Circular economy divided by the total workforce, expressed as a percentage.

Interpretation: Demonstrates the potential for job creation and skills development in fields related to the Circular economy.

Economic Dimension

11. *Earnings before Interest, Taxes, Depreciation, and Amortization (EBITDA)*

Description: This economic indicator evaluates the profitability of Circular economy initiatives by analyzing benefits without considering financial and fiscal impacts.

Calculation: Total revenues minus operating expenses (excluding interest, taxes, depreciation and amortization).

Interpretation: Provides information on the financial sustainability of Circular economy initiatives, supporting strategic decision making.

12. *Circular Contribution Margin*

Description: This indicator assesses the economic viability of circular initiatives by calculating the profitability after accounting for associated costs.

Calculation: Revenues from Circular economy practices minus their operating costs.

Interpretation: Highlights the economic benefits of circular approaches within agribusiness operations.

13. *Circular Economy in Agribusiness Technical Cycle*

Description: This indicator measures the degree of integration of Circular economy principles into the technical and operational infrastructure of the establishment.

Calculation: The proportion of Circular economy compliant processes and infrastructure in relation to total operational elements.

Interpretation: Reflects the systemic adoption of the Circular economy, promoting resilience and innovation in agribusiness systems.

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Chapter 27
Forest-Based Amazonian Bioeconomies: New Opportunities and Old Challenges

Jochen Dürr, Sonia Maria Carvalho Ribeiro, Daniel Vargas, Jorge Sellare, and Jan Börner

27.1 Introduction

The concept of bioeconomy first gained popularity in Europe, where it was proposed as a strategy to replace fossil resources based on new and more efficient uses of biomass enabled by innovations in biotechnology (Patermann & Aguilar, 2018). Alternative early visions of bioeconomy focused on agro-ecological principles (Bugge et al., 2019). Sustainability principles were quickly incorporated in the bioeconomy discourse, but few national bioeconomy strategies paid much attention to the role and fate of biodiversity in bioeconomic transformations, until recently (Dietz et al., 2024). Bioeconomy strategies that massively increase the demand for

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biomass can pose a threat to biodiversity in natural and cultural landscapes. Countries with biodiversity-rich ecosystems, on the other hand, often look at biodiversity as a comparative advantage for bioeconomic transformation (Abramovay et al., 2021; Aramendis et al., 2018; IICA, 2024; Nobre & Nobre, 2019; Queiroz-Stein & Siegel, 2023). Brazil, for example, has coined the term "socio-biodiversity bioeconomy" (Costa et al., 2021, 2022), which emphasizes the sustainable use of biodiversity and the socioeconomic development of local, including indigenous communities as an integrated strategy to conserve tropical forests and traditional livelihoods in the Amazon region (Dietz et al., 2024).

As one of the most biodiverse countries in the world, Brazil has huge potential to embark on a socio-biodiversity-based bioeconomic development pathway. The ecosystem services provided by Amazonian rainforest are valued at between US \$56.72 ± 10 ha^{-1} $year^{-1}$ and US \$737 ± 134 ha^{-1} $year^{-1}$ (Strand et al., 2018). The rich genetic diversity in this ecosystem already provides raw materials for a variety of bioeconomic applications, ranging from pharmaceuticals and cosmetics to sustainable agriculture and biotechnologies. Numerous endemic species and unique bio-physical processes in the Amazon region could become new sources for bionic inspiration and other innovative solutions that mimic natural processes for industrial applications (Nobre & Nobre, 2019). Assuming this potential were tapped without further degrading the ecosystem, tropical forests and the people that directly depend on them could benefit from a bioeconomic transformation. Moreover, tropical forests store massive amounts of carbon, and their conservation thus also contributes to climate change mitigation (Sharma & Malaviya, 2023).

The idea that development based on non-destructive uses of biodiverse forests could reconcile apparent trade-offs between economic development and nature preservation has already been subject to academic debate three decades ago (Arnold & Pérez, 2001). Many bottlenecks of the so-called extractive economies or extractivism, an economic system based on the extraction of natural resources, in this case, NTFPs, have been documented, including incomplete markets, fluctuations in quality and quantity, logistical problems due to long distances, the risk of overexploitation, or power imbalances along the value chains (Lowore et al., 2018). Despite success stories with positive initial effects on forest conservation, few documented initiatives produced lasting positive impacts on local development. However, empirical evidence on the effectiveness of NTFP-based local development is still patchy (Rosenfeld et al., 2024). We also lack reliable data on the economic importance of NTFP, which explains why they are rarely considered in national accounts (Wahlén, 2017).

This chapter looks at what has changed since the early hype around extractive local economies based on NTFP with a specific focus on the Brazilian Amazon. Our main objective is to assess whether conditions have improved for a bioeconomy-based approach to bring sustainable development to the region. We start by sketching how the bioeconomy paradigm has taken hold in the recent debate on sustainable development in the region and how it is linked to the NTFP debate. Section 27.2 synthesizes key elements of the theoretical debate on how specific factors might drive success and failure of a bioeconomy based on NTFP. Section 27.3 uses

publicly available data and different studies to characterize the bioeconomic development potential and challenges in the region. Section 27.4 summarizes main findings and lessons learned.

27.1.1 A Socio-biodiverse Bioeconomy for the Amazon Region

The concept of a "socio-biodiverse bioeoconomy" is currently being advocated as a new economic model for the Amazon. A related core idea is that a socially and environmentally sustainable Amazonian bioeconomy must be based on the use and restoration of "standing forests and flowing rivers" (Abramovay et al., 2021; Garrett et al., 2023). The Institute Amazon 4.0, spearheaded by a group of prominent Brazilian scholars, proposes that this vision can be achieved by harnessing the economic potential of Amazonian biodiversity through the use of new technologies, while acknowledging the value of traditional knowledge (Costa et al., 2022; Nobre & Nobre, 2019). According to proponents, a socio-biodiverse bioeconomy is based on traditional knowledge about the biological diversity of the forest and the ability to learn from nature in order to apply the accumulated knowledge in the production of goods and services for a just improvement of the living conditions of the population (Nobre & Nobre, 2019). It requires investments to promote bio-based added value at local scale and to increase efficiency in supply chains as means to achieve environmental sustainability, ecosystem services, and decarbonization (IICA, 2024; Lesenfants et al., 2024). Apart from strategies that exist for decades, such as agroforestry systems, NTFP extractivism, and ecotourism, proponents also emphasize new applications to add value to known and yet to be discovered biological compounds and biomimetic resources (Costa et al., 2022; Nobre & Nobre, 2019). For example, more than 200 plant species with bioeconomic potential have been identified, of which 20 seem promising to be used for food, cosmetics, perfumery, medicinal, advanced materials, and biotechnology. Many of these have long been used by local communities, who possess traditional knowledge on these plants. Traditional livelihoods have been playing a prominent role in managing the vast Brazilian biodiversity, and this use and management of thousands of different species by traditional communities has been shaping the structure and function of Amazon forest (Ellis et al., 2021; Levis et al., 2017). When traditional communities use a variety of native species as part of their livelihoods, culture, knowledge system and religion, sociocultural and biological diversities merge, as a result, into Brazilian socio--biodiversity (Carvalho Ribeiro et al., 2018, 2020; Carvalho Ribeiro & Soares Filho, 2022). Moreover, there are hidden economic values that can be unveiled by innovative entrepreneurship using new technologies (Nobre & Nobre, 2019).

A number of recent strategies, policies, and initiatives promote socio-biodiverse development strategies in the Amazon. Many of these efforts explicitly aim to reconcile economic development with the conservation of biodiversity and the well--being of local communities. A public sector agenda has been pushed since 2009 through the National Plan for Fostering Socio-Biodiversity Products (PNPSB for its

acronym in Portuguese), which supports local communities through improved access to credit, technical assistance, and the development of new market channels (MMA, 2009). The PNPSB has enabled the implementation of various initiatives led by the civil society and development agencies, such as the German development cooperation, which supports local communities in developing value chains for selected NTFP, including brazil nuts, açaí, cocoa, and pirarucu, a fish species (GIZ, 2023).

The private sector has also invested in the region. For example, the cosmetic group Natura & Co. is known for many products with NTFP components from the Amazon and sustainably produced biomass (Natura, 2018). "Fair deals" with local communities are key elements of its value proposition (Natura, 2018). Natura's project Amazônia Viva targets agro-extractivist cooperatives in the Amazon and uses a blended finance mechanism composed of a revolving fund and a philanthropic fund to increase the efficiency, productivity, operational aspects of these value chains (VERT, 2024).

The Brazilian statistics office (IBGE) reports quantities and value of production for 33 NTFP since 1995. Since 2009, different organizations have been publishing lists of socio-biodiversity products. CONAB (2023) already set a minimum price for 17 species.[1] In addition to these, over 80 species (native and exotic) are included in the Food Agriculture Program (Portaria Interministerial No 284, De 30 De Maio De 2018). It has been estimated that over 2200 Amazonian NTFP exist of which more than 1000 species are edible, and some of which are extremely abundant arboreal species with high quality food potential (Clement et al., 2024).

Despite its ecological and cultural importance, Brazilian biodiversity remains virtually untapped due to insufficient mapping and research programs, inefficient governmental support, and lack of cooperation with global biodiversity markets (Carvalho Ribeiro et al., 2024). While the global biotrade market comprises approximately 3000 wild species, Brazil trades internationally less than a dozen bio-commodities (IPBES, 2022). Moreover, the trade of biodiversity products in Brazil concentrates mostly on raw unprocessed materials (Carvalho Ribeiro et al., 2024). Hence, one of the challenges is to further develop socio-biodiversity chains in a way that goes beyond products and instead focus on traditional livelihoods. There is the need to further investigate the role of new technologies such as Biotechnology (BT) for domestication of a broader range of species and Digital technologies (DT) in order to acknowledge the often invisible role of traditional communities across socio-biodiversity chains.

[1] Açaí (*Euterpe oleracea and Euterpe precatoria)*, andiroba (*Carapa guianensis*), babaçu (*Attalea speciosa*), baru (*Dipteryx alata*), rubber (*Hevea brasiliensis*), buriti (*Mauritia flexuosa*), native cocoa (*Theobroma cacao*), Brazil nut (*Bertholletia excelsa*), palm heats (*Euterpe edulis, Euterpe oleracea, Bactris gasipaes*), macaúba (*Acrocomia aculeata*), mangaba (*Hancornia speciosa*), murumuru (*Astrocaryum murumuru*), pequi (*Caryocar brasiliense*), piaçava (*Attalea funifera*), pine nuts (*Araucaria angustifólia*), pirarucu de manejo (*Arapaima gigas*) and umbu (*Spondias tuberosa*).

In sum, re-energizing the Amazon's local NTFP economies with technological and social innovations has become a powerful development narrative (Nobre et al., 2021; Rosenfeld & Poschen, 2024). However, some analysts also warn that the current socio-biodiverse bioeconomy discourse has yet to incorporate valuable lessons from failed NTFP initiatives (Saes et al., 2023). This includes the common finding that market integration can result in incentives for natural resource overexploitation in NTFP value chains (Belcher et al., 2005; Kusters et al., 2006).

27.2 From NTFP to Bioeconomy

There has been considerable debate about how NTFP ought to be defined (see, e.g., Belcher & Vantomme, 2003). Here, we adopt the early definition by Beer and McDermott (1989) who characterize NTFP broadly as "all biological materials other than timber which are extracted from forests for human use." As with non--normative standard definitions of the bioeconomy, this definition allows for both sustainable and unsustainable patterns of natural resource extraction, processing, and use. It applies to a number of globally traded commodities, such as natural rubber or Brazil nuts, in the same way as it applies to a large number of natural products and their derivatives, which are exchanged on local markets or used for subsistence. It is also broad enough to include potentially new products and natural compounds (for example, for pharmaceutical, nutraceutical, cosmetic uses) under a future bioeconomy development paradigm.

Early proponents of NTFP-based development strategies, focusing mainly on tropical forest regions, had high hopes that further integrating local NTFP producers in regional and global markets could create sustainable synergies between nature conservation and local economic development. This view was soon challenged given case-study based evidence associating NTFP production at commercial scales with forest degradation and the marginalization of local resource users (Arnold & Pérez, 2001).

A recent and comprehensive global review found that most studies looking at ecological outcomes of NTFP use focus on material human needs and predominantly document ecological unsustainability (de Mello et al., 2020). Still, the reviewed literature also documents cases where NTFP use has been economically, socially, and ecologically sustainable and there is no doubt that NTFP use contributes substantially to the income of forest users at global scale (Angelsen et al., 2014). It therefore remains highly relevant to ask whether sustainability gains can be expected from promoting NTFP under a new bioeconomy paradigm. To start exploring this question, we revisit the theoretical foundation of the idea that promoting value chains based on (non-timber) biological materials from forests constitutes a sustainable local development strategy for biologically diverse world regions.

Alfredo Homma (1982, 1993) was one of the first to apply rigorous economic reasoning to this proposition. Timber and non-timber forest products, in Homma's view, follow the same economic dynamics: (1) they rise in response to a particular

demand, (2) grow over time, and (3) stabilize at a certain stage, right before (4) they decline and eventually collapse (Homma, 1993). Homma illustrated these "boom and bust" dynamics by looking at a number of NTFP in the context of the Brazilian Amazon region, including rubber in the nineteenth century, cocoa in the twentieth century, and more recently, to açaí (Homma, 2012). His key insights can be summarized as follows:

1. Given natural conditions, the productivity of NTFP extraction from natural forests tends to be low per unit of land and labor.
2. When domestication is possible, both land and labor productivity of NTFP extraction can be substantially increased.
3. Domestication and intensified production of NTFP requires capital and managerial skills that many local resource users have limited access to.

Growing demand and competition between production factors are key to understanding the underlying economics. In the Amazon, and many other tropical forest frontiers, access to abundant land resources is relatively cheap. The same eventually applies to labor when poor workers migrate into these regions. However, with basic technology and manual labor, the supply of extractive goods remains limited by natural capacity. As increasing demand for forest products elevates prices, capital is attracted to the region. New capital promotes technological innovation, including domestication and cultivation techniques, increasing the productivity of labor and land. As a result, many extractive economies have experienced transitions into more intensive cultivation schemes with potentially adverse consequences for the underlying natural ecosystem (Fig. 27.1).

Historically, these dynamics were often similar regardless of the particularities of the extractive goods with few exceptions[2] (Homma, 2008). Sooner or later, the extractive economy dug its own grave. This process often implied radical changes to the traditional livelihoods of the original extractive communities—if they cannot adapt, it may result in marginalization or migration to neighboring cities (Homma, 2010).

Governance and institutions have an important role to play in co-determining the outcomes of developing NTFP value chains (see Fig. 27.1 lower part). Effective rules for resource access and use can, in principle, mitigate the environmental impacts of developing NTFP value chains. Similarly, proper access to public services and functioning social safeguards could enable extractive communities to successfully adapt to a changing economic environment. However, effective governance arrangements are notoriously hard to establish in most world regions with high potential for the development of NTFP value chains (Arnold & Pérez, 2001; Shackleton et al., 2015).

Early on, Homma emphasized technological change as the other potentially game-changing factor in the quest to promote sustainable development in tropical

[2] Exceptions include those products that do not have economic value or are abundant in nature, or that are, in the short term, unlikely to be substituted by technological alternative. For more information, see Homma (2008, pp. 53–56).

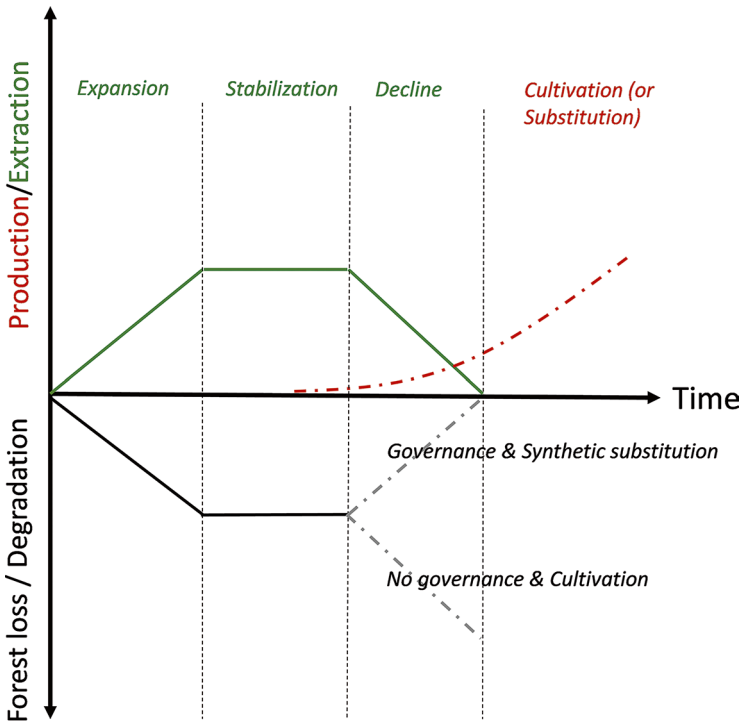

Fig. 27.1 Stylized NTFP production cycle and forest impacts (adapted from Homma, 1993, p. 18)

forest environments, like the Amazon region (Homma, 1993). Technological change can, indeed, strongly affect the conditions and mechanisms described above. Over the past two decades, few technology fields have grown faster than biotechnology and the digital world, including applications in sensing and robotics (McNamee & Ledley, 2012; Mondejar et al., 2021; Morales-Barquero et al., 2019; Oliveira et al., 2021). This has given rise to the idea of bioeconomy as a new development paradigm in many parts of the world and more recently also in the context of the Amazon region (Abramovay et al., 2021). It is thus helpful to systematically discuss how these technological innovation trends alter the prospects of a sustainable NTFP-based economy (see also Table 27.1).

Biotechnology (BT)

Recent developments in biotechnology can potentially alter the systemic relationships in today's extractive economies in the following ways:

1. Faster domestication of a broader range of valuable species facilitates plantation-based NTFP production (Lyzenga et al., 2021; Ramawat & Arora, 2021). While this may come with new local employment opportunities for low to medium skill labor, it also potentially increases the risk of forest loss and degradation if cultivation areas were to expand in an uncontrolled manner. In addition, domesti-

Table 27.1 Synthesis of theoretical effects enabled by technological advances

		Local employment	Domestic value added	Deforestation/ forest degradation
BT	For domestication	Up	Up	(Up)
	For synthetic substitutes	Down	(Up)	Down
	For circularity	Up	Up	(Up)
	For new uses of compounds	(Up)	(Up)	(Down)
DT	For sustainability certification	(Up)	(Up)	(Down)
	For market access and coordination	Up	Up	(Up)
S&R	For improved knowledge about resource availability	Up	Up	(Up)
	For better policy monitoring and enforcement	Down	Down	Down
	For reduced labor costs	Down	Up	Up

Note: Parenthesis indicate that expected effects are uncertain or highly dependent on local context factors

cated species can be transferred to other world regions with appropriate agro-ecological conditions, limiting comparative advantages associated with endemism.

2. Faster development of synthetic variants of a broader range of natural compounds, on the other hand, may decrease the demand for natural compounds (Frisvold, 2023; Voigt, 2020). If synthetic production generates new employment opportunities for high skill labor, it will rarely do so locally at the less developed tropical forest frontiers. While this eventually alleviates pressure on natural forests, it will also likely put a strain on established commercial links between local extractivists and, for example, the pharmaceutical industry.
3. Biotechnology can also enable or speed up the discovery and use of new natural compounds (Afonso, 2022). A wide range of phytochemical compounds can be extracted from Amazonian NTFP and used in the nutraceutical, pharmaceutical and/or cosmetic industries (Wongtschowski et al., 2021). This offers the possibility of high-value low volume production with less impact on the environment. Local impacts will then depend on whether domestication is possible or synthetic substitutes can be developed.
4. Additional local employment and income opportunities potentially arise from new biotechnology-enhanced processes that enable cascading and circular uses of waste streams in NTFP production/processing (Angulo-Mosquera et al., 2021). As long as the resulting demand for secondary (waste) streams does not exceed the demand for primary streams, such innovations could make local NTFP-based economies more sustainable.

Digital Technologies (DT)

Digital world innovations have reportedly transformed some rural economies by dramatically reducing transaction costs (Matthess & Kunkel, 2020). Potential implications for NTFP-based economies include:

1. Improved market access for small producers by reducing administrative costs and facilitating access to credit and information, including extension services (Nwangwu et al., 2024).
2. Better coordination between small-scale producers reducing the organizational costs of rural associations and trade unions with positive effects on their bargaining power in the value chain (Fahmi & Arifianto, 2022).
3. Reduced costs of participation in labeling initiatives, which encourage sustainable production via price premia (Hidalgo et al., 2023).

Many of these benefits depend on access to high-quality digital infrastructure in rural areas and also digitally enhanced local NTFP value chains must be governed by effective rules for resource access and use to develop sustainably.

Sensing and Robotics Technology (S&R)
Sensing technology has been fundamental in improving the environmental governance at the tropical forest margins. In combination with robotics, new sensors could affect extractive economies in the following ways:

1. More frequent wall-to-wall land cover monitoring at high spatial resolutions and low-cost has been key to improve the effectiveness of environmental law enforcement in many parts of the world (Börner et al., 2020; Rose et al., 2015). Improved monitoring tools also facilitate the design and implementation of innovative incentive-based conservation policies and thus represent a key ingredient of strategies to promote sustainable NTFP value chains.
2. In combination with robotics, such as in aerial drones, novel sensors also provide real-time information about the availability and quality of extractive resources and thus facilitate planning and operations in (commercial) NTFP production (Lechner et al., 2020).
3. Robotics applications can also, in principle, improve working conditions in risky NTFP extraction activities (Sparrow & Howard, 2021), but net impacts at the local level will depend on whether the technology becomes affordable for small-scale producers and its impact on labor markets.

In sum, not all current technology trends will naturally work in favor of a new bioeconomy-inspired vision of local sustainable development based on NTFP or "socio-biodiversity" in the global tropics. In fact, a fast biotechnology-propelled transition could, all else equal, fuel the boom and bust dynamics described by Alfredo Homma and leave many local extractive communities worse off than today. The lessons drawn from the critical voices in the NTFP literature thus seem even more important today than before. Strategies to promote local development via the integration of biodiversity-based resources into regional and global markets must be accompanied by gradual improvements in the delivery of basic public services and the design and enforcement of the social and environmental legislation governing natural resource access and use.

27.3 The Development Potential of a Socio-biodiverse Bioeconomy in the Brazilian Amazon

27.3.1 Spatial Patterns of NTFP and Their Values

The traditional collection, processing, and commercialization of products from Brazilian biodiversity is widespread in the 12 million ha of 94 Extractive Reserves (RESEX), conservation units, 355 indigenous lands and 253 *quilombola* territories (maroon descendants), encompassing more than 28 traditional peoples and communities (TPCs), such as *ribeirinhos* (riverine dwellers), rubber tappers and other small landholder communities (Bachi & Carvalho-Ribeiro, 2023; Carvalho Ribeiro et al., 2020, 2018).

To illustrate current spatial patterns of NTFP production, we used the Simpson diversity index (λ) to the recorded NTFP mix in each municipality of the Amazon biome based on IBGE data for 2022 (Eq. 27.1, Fig. 27.2). Our calculation relied on the count and relative quantity collected and traded, above 1 ton, of 33 NTFP (n) for number of municipalities in the biome (N), scaling the index (λ) by 100 to obtain values ranging from 0 (minimum diversity) to 100 (maximum diversity):

$$\lambda = 1 - \left(\sum n\left(n-1\right) / N\left(N-1\right)\right) \times 100 \tag{27.1}$$

As shown in Fig. 27.2, indigenous lands are often located in municipalities with a high diversity in NTFP production. Much of the potential for socio-biodiverse local development in the Amazon is thus concentrated under the stewardship of traditional and indigenous communities. Many of these regions suffer from poor public service delivery and little or no presence of the state and thus currently inadequate conditions for leveraging the sustainable potential of some of the technologies (e.g., BT, S&R) that have been proposed as game changing for the success of socio-biodiversity based development.

Representative information about how NTFP are used and processed in Brazil is limited. A recent study estimated an annual average of US $298 million (for the years 2017–2019) in traded value involving 64 unprocessed NTFP, including fish and agroforestry products (Coslovsky, 2021). In 2023, the New Economy for the Brazilian Amazon initiative projected market values of US $2.5 billion in 2020 (BRL $12 billion) and US $8.1 billion in 2050 (BRL $38.5 billion) across various production chains, spanning primary, secondary, and tertiary sectors (Nobre et al., 2023). This estimation concerns 13 products, including açai (fruit and palm hearts), cocoa, Brazil nut, babaçu (coconut and oil), cupuaçu, honey, rubber, buriti, urucum, copaiba, and andiroba.

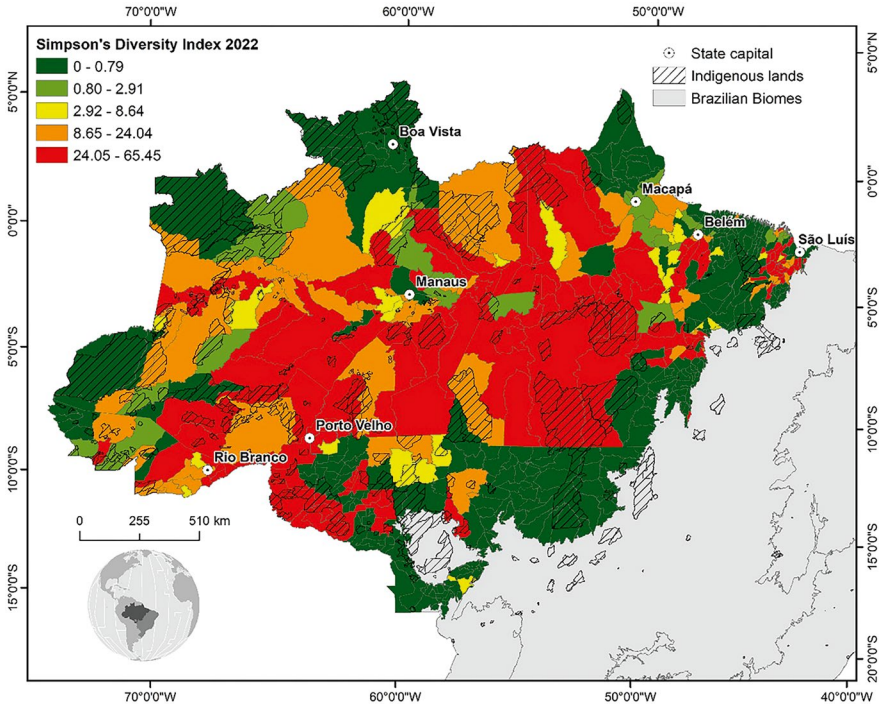

Fig. 27.2 Diversity of NTFP per municipality in Amazon and locations of indigenous lands

27.3.2 Recent Examples of Bioeconomic Innovations and Factors Contributing to Success and Failure

To evaluate if bioeconomic innovations based on NTFP have been successful and which factors influenced success or failures, we first reviewed studies that did a literature review on this topic for the Brazilian Amazon (Afonso, 2022; Rosenfeld et al., 2024), i.e., a qualitative review of literature reviews, and then added more case studies from "grey literature" in Portuguese language that are normally not included in literature reviews. Moreover, we reviewed literature on açaí, the most prominent NTFP in recent years.

Afonso (2022) shows that there have been bioeconomic product and process innovations in the case of açaí, mainly cultivation and processing for exports. Moreover, biotech research has shown new properties of açai such as an ingredient for antiaging cosmetics or for antifungals. Pequi oil has also been shown to have potential for pharmaceutical and nutraceuticals uses, some of which are already used by the Brazilian industry, albeit mainly at the local level. Regarding the main organizational, institutional, and marketing innovations, Afonso (2022) give the examples of the Origens Brasil® network, which promotes sustainable trade of Brazil nuts, and the existence of central cooperatives, which promotes alliances

with national and international companies. Moreover, the above-mentioned PNPSB from 2009 and the Brazilian Bioeconomy Sociobiodiversity Program from 2019 are cited as important political changes that can foster production and commercialization of NTFPs through institutional markets (such as the Food Acquisition Program, PAA), technical assistance and trainings, and the organization of value chains.

Rosenfeld et al. (2024) review 25 studies on NTFPs from 2012 to 2021. The studies focus on projects that supported açaí, Brazil nut, cacao, rubber, and andiroba, mainly in the Federal States of Pará and Acre. The studies attest to some positive income effects of NTFP marketing, but these effects tend to be conditional on the projects also providing subsidies and support to other activities such as sustainable timber management, payments for ecosystem services, or community-based tourism. The effects on forest conservation were positive, but mainly indirect, by strengthening land rights. The authors also highlight some negative impacts of intensified NTFP management on biodiversity. The main factors for success reported are stable and sufficient income from the forest, the legal protection of forest areas, and cultural linkages of NTFP users to the preservation of the forest. Local organizations such as cooperatives, and their collaboration with civil society, private and public entities are important for market entry, and the transfer of knowledge and financial resources are key for success. However, Rosenfeld et al. (2024) criticize the lack of strong evidence both for impacts and success factors and point out that most of the studies lacked robust methodologies for causal inference.

Frizo et al. (2024) monitored 57 local initiatives that work with the NGO Conexsus in the State of Pará. These consist of innovative approaches to strengthen local associations, cooperatives, and small companies, connect them with national and international companies, and articulate strategic partnerships with public and private entities to promote an "ecosystem of community businesses" for the Amazonian socio-bioeconomy. However, the report highlights that those community businesses still lack strategic solutions for their organizational development, and have difficulties ensuring access and continued provision of essential services for their businesses. Especially, a lack of organization and networking for market access, missing land tenure regulations, financial restrictions, lack of technical assistance, and difficulties in participating in institutional markets such as PAA are mentioned (Frizo et al., 2024).

Through PNPSB implementation, the Ministry of the Environment (MMA) has been working together with NGOs to promote local clusters of production (APL for its acronym in Portuguese), which support socio-biodiversity products and try to facilitate access to diversified markets. Despite this institutional support, an evaluation of 27 of those initiatives shows that they are still confronted with lack of access to and scarcity of biodiversity resources, seasonality of production, and difficulties in scaling production. Moreover, prices received are often low, and they lack appropriate technologies, basic infrastructure, and equipment for processing and transporting their products. The local organizations often have insufficient working capital, high costs, low management capacity, and difficulties in meeting legal formalities and hygiene requirements (MMA, 2017).

Wongtschowski et al. (2021) reviewed scientific articles to identify promising research related to inputs from Amazonian biodiversity, including diverse themes such as: health (cancer treatment, traditional medicine); food and agriculture (functional foods, crop protection and improvement); green technologies and sustainability (sustainable construction, clean energy, waste reduction and revaluation, and resource optimization); and new materials (biopolymers). They emphasize seven studies as particularly promising, including biopolymers from Amazon turmeric (*Curcuma longa* L.), cancer therapy from Amazon fruits, extraction of cellulose from the tucumã's (*Astrocaryum vulgare*) endocarp, and textile fibers from palms for sustainable construction.

Finally, the case of açaí deserves special attention as an exemplary recent success story with certain caveats. Açaí (*Euterpe oleracea Mart*) is a palm tree native to the Amazon estuary and its fruits form part of the traditional Amazonian diet. Following increased national and international demand as a supposed superfood, extractivist production more than doubled from 108,000 to 239,000 tons during 2007–2023 (IBGE, 2008, 2024) mostly through intensified management practices. However, by far the largest increase was in plantations, which already reached 233,000 ha producing 1,700,000 tons of açaí in 2022 (IBGE, 2024). This led to increased income for riverine açaí producers and to the establishment of a processing cluster around the city of Belém (Costa et al., 2018). The factors for this success were the increased national and international demand, which met already established strong local markets, with a sophisticated web of intermediaries. However, the local processors are not very innovative and there is a risk that big monoculture plantations with their own processing facilities will push them out of the market (Vanni, 2018). Açaí grown together with a variety of annual or perennial crops can contribute to the creation of wealth in rural areas while enriching the multi-functionality of spaces (Euler et al., 2019; Lopes et al., 2019).

However, there is another side to the açaí story. Recent research suggests that increases in the density of açaí palm can lead to significant changes in the structure of forest land, reducing tree abundance and functional richness by half (Freitas et al., 2021). Tree density and biodiversity decline continuously as açaí cluster density increases. Some forest stands are so dominated by açaí that they are almost devoid of other tree species. These findings challenge current practices and regulations for açaí management and therefore require better regulation of NTFP extraction to avoid potential ecological disasters (Freitas et al., 2021). Similarly, the data of Damasco et al. (2022) show that managed açaí areas have much lower tree species richness than unmanaged areas. Also, that there is a clear negative correlation between species richness and the density of açaí clumps. Campbell et al. (2018) analyze the effects of intensified açaí farming practices on pollination services and conclude that high density of açaí palm leads to a reduction in this ecosystem function and an increase in the presence of antagonistic species, such as ants. These negative impacts have been corroborated by other studies that also focused on the effects of açaí plantations on forest composition structure (Barros et al., 2024; Freitas et al., 2015), seed rain and soil seed banks (Silva et al., 2023), and carbon emissions (Lira-Guedes et al., 2021). Furthermore, some studies suggest that areas

with açaí monocultures are more prone to outbreaks of malaria and higher incidence of Chagas disease (Silva, 2018; Souza et al., 2019). Lastly, despite some evidence pointing toward the benefits of açaí production to the livelihoods of local communities in the Amazon, other studies present evidence for negative impacts on socioeconomic outcomes. These studies argue that inequality is still rampant in açaí value chains, with the local communities receiving only a fraction of the price paid by the final consumers (Pegler, 2015; Vanni, 2018), and that child labor, although embedded in the local culture, represents violations of international agreements (Santos et al., 2023).

In summary, there are many new initiatives and innovations for the development and commercialization of NTFPs, but they often struggle to overcome the old, well-known structural problems. Açaí stands out as a case where market forces have created a profound impact on local economies, albeit at the expense of biodiversity, much in the way predicted by Alfredo Homma.

27.4 Lessons Learned and Implications

The socio-biodiverse bioeconomy narrative clearly offers an attractive new vision for sustainable development in the Amazon. After reviewing the main propositions of this narrative, we find that it still lacks convincing answers to some of the well-documented challenges of bringing sustainable development to tropical forest frontiers. The game-changing technological advances, which gave rise to bioeconomy as a development paradigm in Europe and other industrialized world regions, imply both opportunities and risks for socially inclusive development in the Brazilian Amazon region. In Sect. 27.2, we argued that some of the opportunities (e.g., new uses of genetic diversity, better monitoring, and improved communication) may be new, but that most of the risks (e.g., environmental degradation and marginalization of traditional populations) are known. In Sect. 27.4, we showed that these risks remain highly prevalent in today's NTFP value chains, but also that they can be addressed by carefully designed, locally adapted interventions.

While Clement et al. (2024) characterize these risks as inherent "limitations of neoliberal capitalism," we prefer to frame them as governance challenges that can be overcome if decision-makers are willing to learn lessons from past experiences. We nevertheless fully agree with Clement et al. (2024) that a technology-enhanced Amazonian bioeconomy can only become socially and environmentally sustainable if accompanied by a transformative governance strategy with effective enabling and regulatory components (Stark et al., 2022).

The lessons from decades of promoting NTFP value chains across the tropics are a good starting point for the development of a new bioeconomy governance for the tropics. Key among these lessons is the need for governance to anticipate the social and environmental impacts of exposing traditional resource users and their social-ecological systems to new technologies and market forces. This includes, apart from a transparent and participatory development of access and benefit-sharing

arrangements, effective social safeguards and regulations, as well as incentives for natural resource use. Such conditions for what could be called a "safe bioeconomic operating space" are unlikely to emerge at scale or overnight. In fact, markets and technology often find opportunities much faster than governance can address their undesired consequences. Sustainable bioeconomic transformation at tropical forest frontiers like the Brazilian Amazon region thus likely requires an evolutionary territorial development approach (Torre, 2023). Such an approach must carefully align political support for technology dissemination and market integration with improved public service delivery and strong, locally adapted institutions to safeguard human rights and the environment. In addition to government regulation, private certifications can also play an important role in protecting biodiversity. For example, certifications can lead to greater valorization and improved management of açaí among smallholder producers, thereby contributing to biodiversity conservation. However, the expansion of commercial açaí plantations should be more strictly regulated to ensure forest protection (Damasco et al., 2022).

The role of science in this process cannot remain limited to research and development. Instead, science must provide the systematic evidence base for a continuously evolving transformative governance. This goes beyond improving the still patchy knowledge base on NTFP potential or use and includes rigorous counterfactual impact evaluations of policy instruments, or mixes thereof, aimed at making local bioeconomies inclusive and environmentally benign. To do so, both government and civil society must open up to a transparent culture of learning that embraces evaluation as a means to enhance positive impacts for their constituencies.

Ratcheting up the transformative forces of governance seems urgent amid recent trends in the Amazonian NTFP economy. Rising demand has increased the output of many NTFPs over the last two decades, while productivity has stagnated between 2006 and 2017 (Costa, 2021, 2024; Deus, 2023). Rising prices reward producers at the expense of local consumers. At the same time, extractivist agroforestry systems lost importance in smallholder production systems, while production systems based on intensification and plantations of permanent trees and crops have become predominant. As cattle ranching and permanent crop monocultures have also gained importance in these production systems they have become environmentally less sustainable over time (Costa, 2024). Additional pressure from future climate change on these production systems and the relative productivity of NTFPs vis-à-vis cultivated crops yet have to be factored into most current predictions of future bioeconomic potential (Brandão et al., 2021).

Moreover, even if more, and also more diverse, NTFPs are traded on Brazil's local markets today than three decades ago, the economic benefits generated by these markets still do not seem to tangibly improve the livelihoods of the traditional and indigenous communities that live in the most biodiverse parts of the country (Carvalho Ribeiro et al., 2018, 2024). The role of these communities as natural resource stewards has been well documented in the literature on forest conservation (Börner et al., 2020). Beyond its contribution to nature conservation, this natural resource stewardship and the associated traditional knowledge represent an important asset for the vision of a socio-biodiverse Amazonian bioeconomy. This

warrants stronger public support beyond measures to strengthen NTFP value chains, including improvements in public service delivery and proactive involvement of traditional and indigenous communities in locally adapted governance arrangements for sustainable bioeconomic development.

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Chapter 28
Sugarcane Bioeconomy and Circularity in Latin America: Progress and Future Pathway

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28.1 Introduction

There is growing recognition of the need and urgency to base the economy on renewable resources (Bioeconomy) and for the whole process to have the lowest environmental impact possible (circular) in terms of using residues, attaining efficiency, using bioenergy, and having low GHG emissions. Sugarcane is a millennial crop that can contribute to all those aspects and, thus, be part of the plethora of resources that humanity needs to develop or enhance to solve the immense sustainability challenges. The objective of this chapter is to showcase the main products that stem from the processing of sugarcane in Latin America as well as the important advances in circularity/sustainability. In this region, several initiatives related to the circular bioeconomy are already being implemented. A notable example is the

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use of sugarcane residues, such as bagasse,[1] to generate biogas and electricity. This allows the production of clean energy that supplies the sugar mill plants themselves and provides electricity to the national grids, facilitating access to this energy for the Latin American population. This electricity cogeneration reaches an annual total of approximately 25,445 GWh (UNALA, 2024b). In addition, residues are converted into organic fertilizers, improving soil fertility and reducing the need for chemicals. Sugarcane by-products are also being used in the production of paper, bioplastics,

[1] Dry pulpy fibrous material that remains after crushing sugarcane stalks to extract juice.

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and ethanol as a biofuel, a crucial source that reduces dependence on fossil fuels and contributes to the reduction of GHG. Regionally, around 33.5 billion liters of ethanol are produced annually (UNALA, 2024b).

Three main sections have been defined: (a) examples of progress on circularity around the main areas of environmental concern in the cultivation of sugarcane; (b) sugarcane as a raw material and as a source of bioenergy; and (c) progress and future perspectives. In the latter, a reflection on how to reach the potential of sugarcane to contribute to a circular bioeconomy is included. The text draws on cases and examples of some Latin American countries, which are a way to illustrate the main arguments. It is not, however, an assessment of the status quo of circularity in the sugarcane sector in Latin America. It will be argued that a firm starting point would be to examine the state of adoption of good practices and how those adopted can shed light on what can be done to maximize the potential of this crop not just in Latin America but in all the countries in which it is cultivated.

28.2 The Importance of Sugarcane in Latin America

The sugarcane agro-industry is a key actor for sustainable development in Latin America. It is a source of employment, economic diversification, foreign exchange, investment attraction, and innovation. Not only does it contribute to increasing exports of Latin American economies, but it also creates direct and indirect employment

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Table 28.1 Sugarcane cultivation in Latin America

Country	Hectares harvested	% of national land
Argentina	400,000	0.14%
Brazil	10,000,042	1.20%
Colombia	193,003	0.17%
Costa Rica	54,848	1.07%
Dominican Republic	32,467	0.67%
Ecuador	80,000	0.28%
El Salvador	77,827	3.70%
Guatemala	250,000	2.30%
Mexico	806,193	0.41%
Nicaragua	72,600	0.56%
Peru	84,941	0.07%

Source: UNALA (2024a)

opportunities, with potential for growth and investment attraction in related sectors. According to data from the International Sugar Organization (ISO), about 47% of sugar exports worldwide come from the region (ISO, 2023). In addition, millions of people are involved in the agro-industry's supply chain. It is estimated that the Latin American sugarcane sector generates approximately 6.4 million jobs (UNALA, 2024b). Additionally, the production of sugar and its by-products, like ethanol and electricity from sugarcane bagasse, helps diversify regional economies.

Besides economic benefits, this industry has made contributions in terms of the environment. The use of sugarcane bagasse for electricity cogeneration reduces reliance on fossil fuels and lowers GHG emissions. Furthermore, by-products of sugarcane are utilized to create other derivatives, such as ethanol, a renewable fuel that helps decrease polluting emissions. Together, Latin America produces about 30% of ethanol worldwide each year (ISO, 2023), virtually all from sugarcane. This is achieved through the utilization of 12,051,921 ha of land, accounting for 0.07–3.7% of the national territories, as detailed in Table 28.1.

There is a social component in the relevance of this agro-industry. Apart from direct and indirect jobs, there are social initiatives in place led by sugarcane companies in their area of influence. These programs range from the implementation of best practices with small and medium sugarcane suppliers, to the development of key social infrastructure, such as schools and medical clinics. Some of these projects are implemented in partnership with national and local governments. In other cases, there are social programs implemented with fully private participation, showing the commitment of Latin America's sugarcane agro-industry to neighboring communities.

28.3 Sugarcane as a Sustainable Crop and Progress on Circularity

Sugarcane cultivation, as with any human activity, can have negative impacts on the environment in areas such as water use and pollution, air quality, deforestation, and soil degradation. However, there are numerous ways in which environmental impacts can be substantially reduced. This industry has examples in all components of circularity: resource use efficiency, use of biological options, reuse of liquid and solid waste, renewable energy through biomass use, and even natural resources restoration in its area of influence. In this section, the main mechanisms in Latin America to optimize the use of resources and pollution control are presented. We argue that the sugarcane agro-industry has several examples of circularity and that it is headed towards a sustainable future. This is not to say it does not affect the environment, but rather that there is great potential when adopting existing practices by all producers on the continent. Only some specific cases will be mentioned and cited though there are more in the region.

28.3.1 Water Management

Agriculture is the biggest water user in the world with an estimated 70% use of all water withdrawals globally (FAO, 2021; World Water Assessment Programme, 2009) though there are variations between different continents. While North America and Europe use around 50% of water withdrawn for agriculture (with industry being their biggest user), the percentage in Africa, Oceania, Asia, and Latin America varies from 70 to 90% (FAO, 2021).

Sugarcane has a small water footprint compared to other crops (Mekonnen & Hoekstra, 2014), but since it is one of the main crops worldwide, it is also an important water user. Its impact on the environment depends on how it is used as well as on the treatment of wastewater. Advances have taken place, as the following examples of sustainability through water management will suggest.

The volume of water used for sugarcane cultivation varies between countries. The water footprint indicates the volume used per unit of production (i.e., m^3 of water per ton of sugarcane). Hoekstra et al. (2011) proposed three components of the water footprint, namely: blue water footprint, which is that withdrawn from surface and ground sources and applied as irrigation; the green water footprint, which is that covered with rainfall; and the gray water footprint, which refers to the volume of water needed to dilute the most abundant pollutant. Table 28.2 shows the water footprint estimated for different countries across Latin America and how they compare to global values. These important differences are related to location and their rainfall levels, crop yield differences related to management, and irrigation technology.

Table 28.2 Water footprint of sugarcane in Latin American countries compared to the global mean (m^3/ton)

Country/region	Green water footprint	Blue water footprint	Gray water footprint	Total water footprint	Source
Mexico				274	Garay Jacome et al. (2022)
Peru		134	8	142	Mekonnen & Hoekstra (2011) in Scarpare et al. (2016)
Brazil	79	28	14	121	Scarpare et al. (2016)
Guatemala	94	19	6	119	ICC (2024a) (2023
El Salvador	105	10	3	118	ICC (2024a)
World average	139	57	13	209	Mekonnen and Hoekstra (2014)

There have been advances in irrigation efficiency in Latin America. Technology has played a major role and efficiency values vary from 30 to 40% in the case of inundation or furrow irrigation, to more than 90% in drip irrigation (Torres Aguas, 1995). As producers shift to those irrigation technologies, their water use declines. Technology and science have also played a role in better water use through the estimation of crop water demand according to temperature, rainfall, soil type, and wind speed at the local level. There are software programs, such as Cengiriego in Guatemala (CENGICAÑA, 2018) and Gerenciamento Integrado de Riscos Hídricos e Ambientais (GIRHA) in Brazil, that indicate the right amount of irrigation sheets for plots daily. Weather stations and soil humidity sensors are used to feed information into the software. In Colombia, by using the Water Balance Estimation tool to measure and control water consumption in the fields, the sugar agro-industry has managed to reduce its water consumption in sugarcane production by 50% (UNALA, 2025). A third defining factor in efficiency is irrigation canals.

The impact of water use in the industrial processing of sugarcane can be reduced considerably. The first step is to reduce general use, which can be done with the use of technology to clean sugarcane before crushing it without using water. In the case of São Paulo, water demand decreased by 85% from the 90s to 2024, as seen in Fig. 28.1 (Governo do Estado de São Paulo, 2024). The second general step is to reuse water in the different processes. Cooling systems are widely used in countries like Argentina, Brazil, Colombia, El Salvador, Guatemala, Mexico, and Peru. Water treatment plants are also used to remove certain components so that water can be further re-used in other processes. For example, Leales Sugar Mill's (Argentina) commitment to sustainability in sugar, alcohol, and energy production has estimated a total 35% reduction in water consumption per ton of cane milled since Leales Mill was acquired by *CIA. Inversora Industrial S.A.*—CIISA in January 2010 (ComunicarSe, 2013).

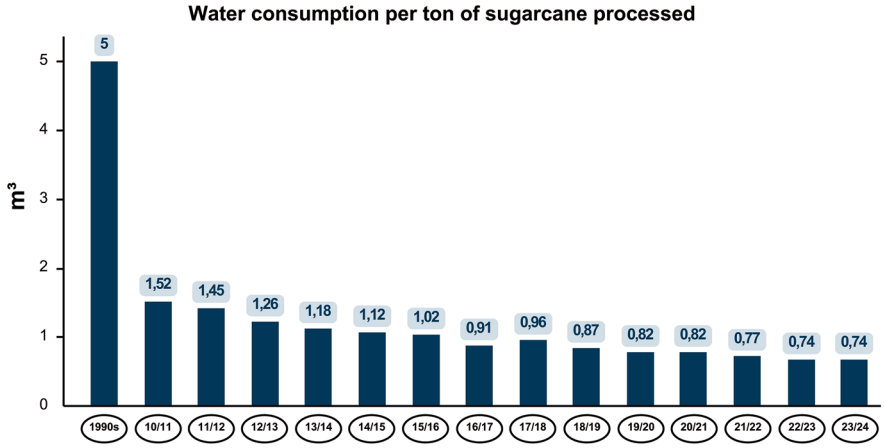

Fig. 28.1 Water consumption per ton of sugarcane processed in São Paulo (m^3/ton) per milling year. Source: Governo do Estado de São Paulo (2024)

The third main action is to use wastewater for fertigation,[2] so that it is not discharged into rivers. It does, however, require treatment before it is used for that purpose. The benefits for the environment are more than twofold. On the one hand, water demand reduction entails less pressure on water sources, and in some companies (ICC, 2023), the industrial component in the water footprint of sugar comprises around one percent. On the other hand, wastewater treatment and its use for fertigation prevents pollution in rivers.

Between 1990 and 2023, in the state of São Paulo alone, the sugar-energy sector reduced absolute water demand by approximately 60%, while sugarcane production increased by about 150% during the same period. This result was achieved through a series of investments, notably the closing of industrial water circuits, the elimination of burning as a pre-harvest agricultural method—thereby ending the need to wash the sugarcane before processing—and fertigation using vinasse (Governo do Estado de São Paulo, 2024). Grupo CASSA, the biggest sugar producer in El Salvador, reported a 71.6% reduction of industrial water use in the period 2015–18, and 97% of water recycling (Grupo CASSA, 2018).

There are several examples of the contributions of the sugarcane companies to integrated water resource management, including some outside their chain of production. They are related to watershed management and include forest protection and restoration, soil conservation, disaster risk reduction, and scientific data generation (weather and river flow). Specific cases are the Water for Life and Sustainability Fund in Colombia (Moreno, 2016) and the Integrated Watershed Management program of the Climate Change Research Institute in Guatemala (ICC, 2024a). *Compañía Azucarera Salvadoreña*—CASSA Group in El Salvador has also funded

[2] Fertigation is the application of fertilizers through irrigation system and is the most advanced and efficient practice of fertilization (Kant & Kafkafi, 2013).

and managed initiatives directed toward communities in their surroundings (ICC, 2024a, 2024b).

A water governance case involving the sugarcane agro-industry of Guatemala was highlighted in the latest report of the Intergovernmental Panel on Climate Change -IPCC- (Castellanos et al., 2023). Following a water crisis associated with the very intense El Niño event that took place from November 2014 to May 2016 (CIIFEN, 2016; NOAA, 2019), dialogue roundtables were established and managed to recover two main rivers in the Pacific lowlands (Gobernación de Escuintla et al., 2017). Local agreements involving a diverse set of stakeholders have been key for effective water management despite the lack of water authorities and legislation. Similar actions have been key for flood risk management too, which was also mentioned in the IPCC report.

28.3.2 Biofertilizers and the Use of Sugarcane Residues as Compost

Sugarcane is a crop with a high biomass production capacity, associated with its long growth cycle, leading to high requirements for both water and nutrients. The application of chemically synthesized fertilizers has, historically, been necessary to sustain profitable production. However, the large-scale application of fertilizers entails economic and environmental costs, since both its production and application generate large quantities of GHG and other impacts on soil and water (Romero et al., 2009).

Biofertilization is currently the most promising alternative to reduce or eliminate chemical fertilization without affecting sugarcane productivity. Biofertilizers are biological products containing living microorganisms, such as fungi and bacteria, that promote plant growth through various mechanisms, including biological nitrogen fixation, phytohormones and siderophores production, phosphorus solubilization, induction of defense mechanisms, among others. Those used in sugarcane consist of plant growth promoting bacteria (PGPB) belonging to *Pseudomonas*, *Gluconacetobacter*, *Azotobacter*, *Burkholderia*, *Herbaspirillum*, and *Azospirillum* genera, which can enhance plant nutrition and growth mainly through biological nitrogen fixation and phosphorus solubilization. However, thanks to advances in agricultural biotechnology, new genera and species of PGPB associated with sugarcane and novel growth promotion mechanisms are constantly being discovered, working synergistically (Zahid et al., 2015).

Biofertilizers have demonstrated significant potential to reduce the needs of fertilizers and enhance sugarcane productivity across Latin America. Brazil leads the development and massive application of fertilizers to sugarcane plantations. Bioinputs based on *Azospirillum brasilense*, which provides up to 70% of the plant's nitrogen needs, have permitted production of up to 100 tons/ha/year with low doses of nitrogen (50–60 kg/ha/year) and with no evidence of depletion of this element in

the soil (Rivera-Urbalejo et al., 2017; Velasco-Velasco 2014). The sugarcane agro-industries of Argentina, Brazil, Colombia, Dominican Republic, Ecuador, Guatemala, Mexico, Nicaragua, and Peru have implemented biofertilizers to their production processes.

In Tucumán, Argentina, the adoption of biofertilizers has become a widespread practice among the productive sector during recent years. Currently, over 65% of the sugarcane fields in the province are fertilized annually with these bioproducts, significantly reducing the use of chemical fertilizers in the agronomic management of the crop (Leggio Neme et al., 2023). Nevertheless, further research and extension of these technologies are needed to integrate them into conventional management practices and move towards a sustainable production system.

In Costa Rica, promising results were observed in Carrillo County, Guanacaste, where a biofertilizer mixture, including *Azotobacter chroococcum* and several strains of *Bacillus*, combined with half the normal nitrogen dose, achieved yields comparable to those obtained with full nitrogen application. The Department of Research and Extension of Sugarcane (DIECA) of the *Liga Agrícola Industrial de la Caña de Azúcar* (LAICA) has played a pivotal role in advancing this research in the crop. Through rigorous bioprospecting and greenhouse trials, promising bacterial strains have been identified for improving sugarcane growth under reduced fertilization regimes of up to 50%. These trials have validated that certain bio inputs can maintain high productivity while significantly reducing the use of synthetic fertilizers (DIECA, 2023). This research underscores the viability of biofertilizers in enhancing the growth and productivity of sugarcane, combined with the mitigation of externalities to soil, water, and environment.

Compost from Mill Muds and Other Solid Residues from Sugarcane

In the sugarcane agro-industry, organic residues are used, such as mill muds (also called filter cake), ash from the washing of chimney gases, bagasse, and sugarcane trash, in mixtures that proportionally can also absorb a certain percentage of the vinasse produced (Sotomayor et al., 2019). The final product can be used as an organic amendment in agricultural fields, providing nutrients such as potassium in important quantities or nitrogen and phosphorus in smaller quantities, depending on the proportions of raw material used in the process.

In São Paulo, CETESB—Environmental Company of the State of São Paulo recognized the agronomic benefits of using organic residues, such as filter cake and ash, by publishing a regulation with general guidelines for their use (Directorate Decision No. 126/2021/P, dated December 16, 2021). These guidelines establish the technical procedure for the application of residues generated in ethanol and sugar production plants and for the licensing of waste mixing yards.

In the case of Argentina, the Obispo Colombres Agro-industrial Experimental Station provides technical assistance to sugar-alcohol companies for the analysis of raw materials, formulation of compost heaps, physicochemical control of the process, evaluation of its stability at the end of the process and evaluations so that its dosage on arable or non-arable land is carried out with the best possible use. Efficient

compost application practices would allow, on the other hand, at least partial substitution of the use of fossil fertilizers on arable land.

Vinasse

Vinasse is a liquid by-product of ethanol production rich in minerals and organic matter. It is used as a fertilizer applied directly in liquid form (diluting it first with water) or in solid form after going through a process of treatment, often adding other nutrients. For every liter of ethanol produced, about 12 L of vinasse are generated, making it a sustainable solution for nutrient replenishment (Silva et al., 2014)

Vinasse holds significant potential for energy production. It is composed mainly of potassium (3340–4600 mg/L K_2O) and sulfur (3700–3730 mg/L SO_4); however, significant amounts of phosphorus (9–200 mg/L P_2O_5), carbon (8700–12,100 mg/L C), nitrogen (480–710 mg/L N), calcium (1330–4570 mg/L C), and magnesium (580–700 mg/L MgO) can also be found (Pinto in Barbosa Cortez et al., 2020). Vinasse can be converted into biogas, biomethane, and bioenergy through biodigestion, a process that maintains its fertilizing properties while producing clean energy and water, aligning with the biorefinery model (de Carvalho et al., 2023). An example of this is Magdalena, one of four ethanol producers in Guatemala that built the biggest biodigesters in the country to extract methane from vinasse for use in electricity generation (Alvarado, 2023).

Currently, Brazil already has numerous biofertilizer factories using vinasse, attached to sugarcane processing plants, with increasing investments in the production of biogas and biomethane as well. Major industry groups already operate industrial plants, such as Raizen, Cocal, and Tereos, with installed capacity ranging from 5 to 21 MW of electricity and more than 25,000 Nm^3/day of biomethane per plant. New projects are also announced annually, such as those by the São Martinho Group, further consolidating another renewable energy production route from sugarcane. Vinasse is also being used as a fertilizer in the sugarcane growing process in Argentina, Colombia, Dominican Republic, Guatemala, Mexico, Nicaragua, Panama, and Peru.

28.3.3 Biological Pest Control and Disease Prevention

Biological control is based on regulating pests through natural agents such as predators, parasitoids, and pathogens, which is considered ecologically and economically sound (Gangwar, 2017). The implementation of these methods began in Costa Rica in the 1980s with the support of the Liga Agrícola Industrial de la Caña de Azúcar (LAICA), which established programs to control the common stalk borer (*Diatraea* spp.) and the spittlebug (*Aeneolamia* spp., *Prosapia* spp.) using parasitoids and entomopathogenic fungi, respectively (Rodríguez-Morales & Chaves-Solera, 2020).

LAICA's Biological Control Programs have been led by the Department of Research and Extension of sugarcane (DIECA) and have allowed the coverage of extensive cultivation areas, benefiting both large mills and independent producers,

with the releasing of 809.93 million parasitoids and the application of 498,375 kg of entomopathogenic fungi between 1984 and 2020 (Rodríguez-Morales & Chaves-Solera, 2020). National average control over the sugarcane borer (*Diatraea* spp.) after 40 years of constant releasing of the parasitoid *Cotesia flavipes* has been established at 30.2%, considering only one application; but, in areas where two applications have been made, the control reached 60%. In addition, different natural enemies contribute to control at the border with another 10%; that's the case of tachinid fly (*Billaea claripalpis*) and braconid wasps (*Alabagrus* sp. and *Agathis* sp.). On the other hand, control level by *Metarhizium anisopliae* over the spittle bug (*Aeneolamia* spp., *Prosapia* spp.) in a period of 15 years reached 57.4%, with a maximum of 87.1% in 1996.

This approach has significantly reduced the use of chemical pesticides, preserved several natural enemies, which contribute to 10% control for the border (mainly tachinid and braconid parasitoids), and promoted a sustainable practice aligned with the principles of bioeconomy, which seeks to reduce reliance on fossil resources and foster more sustainable agricultural practices. In Guatemala, adoption has been widespread through research capacity building and investments by CENGICAÑA and the sugar producing companies since the 1990s (CENGICAÑA, 2014).

Biological control programs have not only improved pest management but also contributed to the environmental and economic sustainability of sugarcane cultivation in most Latin America countries. However, without proper risk management and monitoring, these programs may have unforeseen consequences, such as invasive potential and the spread of diseases.

28.3.4 Greenhouse Gas Emissions (GHG) and the Carbon Footprint of Sugarcane

One of the most used indicators associated with life cycle analysis is the carbon footprint. This measures the total GHGs released into the atmosphere, both directly and indirectly, due to human activities. In 2019, it was estimated that 22% of all GHG emissions came from agriculture, forestry, and other land uses, though with more uncertainty than in other sectors due to the high share and uncertainty of CO_2-LULUCF emissions (Shukla et al., 2023).

The carbon footprint of cane sugar is between 0.24 and 0.76 ton CO_2e/ton sugar (CEFS, 2012; de Figueiredo et al., 2010; García et al., 2016; ICC, 2023). It is estimated using the IPCC guidelines, which define the main components in the whole lifecycle: land use change, fossil fuel use in transportation and agricultural activities, fossil fuel use for irrigation pumps, preharvest and postharvest burning of sugarcane, electricity use (self-generated or purchased from the national grid), nitrogen-based fertilization, and methane from wastewater treatment facilities (IPCC, 2006). In the case of Guatemala (ICC, 2023), 66% of the carbon emissions

correspond to processes in the field, whereas transportation of cane accounts for 9% and the industrial process for the remaining 25%.

In Argentina, the agricultural, livestock, and forestry sector is responsible for 37% of reported emissions and faces the challenge of adapting to climate change while ensuring food security. Among productive activities, the sugar-alcohol agro-industry is of significant economic and social relevance in northwestern Argentina, with Tucumán province having a net harvestable area for the 2024 crop of 294,470 ha. A study to estimate GHG emissions was conducted based on two agricultural systems, on using calcium ammonium nitrate (CAN) as an n-based fertilizer and another using urea. Total GHG emissions using CAN were 28.8 kg CO_2eq/ton cane, and 36.1 kg CO_2eq/ton cane when using urea. Emissions per unit area were 1848 kg CO_2eq/ha with CAN, while with urea they totaled 2317 kg CO_2eq/ha. In Guatemala, emissions per hectare were estimated at 3900 kg (ICC, 2024a, 2024b) and 3002 for El Salvador (ICC, 2023).

Studies in some countries have shown that fossil fuel use is the main source of emissions in the sugar production process, followed by N-based fertilization and pre-harvest burning. Fossil fuels, mainly diesel, are used for agricultural activities, transportation of cane and sugar, and for irrigation pumps. Another factor that can vary and determine emissions is the source of electricity for internal uses. In sugarcane growing countries, it is a widespread practice to generate their own electricity using bagasse and, thus, their carbon footprint is much lower than in those countries where they use other sources, especially non-renewable ones. Mitigation strategies and plans need to tackle the main sources of emissions mentioned above before considering external projects. In terms of emissions, what is valuable in the sugarcane sector is the generation of bioelectricity and biofuels, which will be explained later in the chapter.

At the country level, an initiative in Costa Rica is worth highlighting. Under the concept of Nationally Appropriate Mitigation Action (NAMA), part of the Paris Agreement and the UN Convention on Climate Change, it is a public–private partnership to reduce GHG and promote sustainable practices. It includes capacity building for sustainability; establishing mitigation targets for the chain of production; implementing good practices and technological actions to improve productivity, reduce costs, increase profits and reduce environmental impacts; and generating a differentiated product, the "low emission sugar" (LAICA, 2023).

28.4 Sugarcane as a Raw Material and as a Source of Renewable Energy

Sugarcane can contribute greatly to the bioeconomy for two main reasons. In the first place, a vast number of products can be manufactured from all parts and by-products of sugarcane, from the juice, bagasse, sugar, molasses, mill muds, vinasse, and trash. The products span from food, beverages, pharmaceutical uses, fertilizers, animal feed, fuels, bioplastics, packaging, cosmetics, and more, as Fig. 28.2 shows.

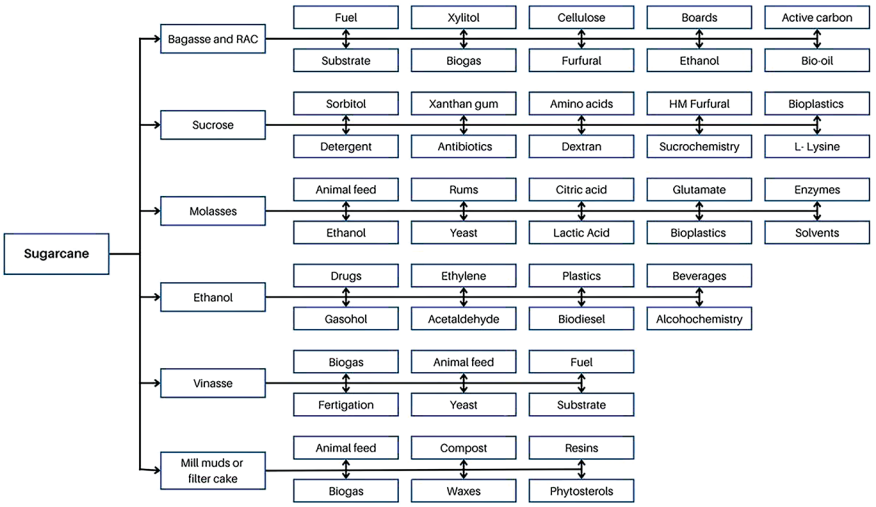

Fig. 28.2 Main products from sugarcane and its derivatives. Modified from Aguilar Rivera (2009)

Most importantly, many of those products are produced from oil derivatives at present, so sugarcane presents an opportunity to replace them. Secondly, it contributes to bioenergy generation through electricity from bagasse (mainly), and through ethanol, which is used to replace a certain percentage of gasoline in many countries, though it can be used as the only fuel in some cars. The main products and uses of sugarcane as a raw material will be presented next. Again, only a few examples are included for the purpose of illustrating progress to date and future potential.

28.4.1 Bioelectricity

Bagasse is a fibrous material that is composed of the external part of the cane. The mean composition of washed–dried bagasse is cellulose (45–55%), hemicellulose (20–25%), lignin (18–24%), and ash (1–4%) (Payá et al., 2018). Sugarcane bagasse, with its high energy potential, has proven to be an important renewable energy source, by turning what would otherwise be waste into a valuable resource, the sugarcane industry drives sustainable development and fosters a circular economy within the sector.

The process of energy generation from bagasse involves burning the material to produce steam, which powers turbines that generate electricity. This cogeneration method is highly efficient, as it simultaneously produces electricity and heat for industrial use (CENGICAÑA, 2014). Not only is this process clean—since the carbon released is offset by the carbon absorbed by growing sugarcane—but it also significantly reduces waste and emissions.

The environmental benefits of producing electricity from sugarcane bagasse are remarkable. Unlike fossil-based energy sources, sugarcane absorbs CO_2 during its growth in the field, effectively sequestering carbon rather than releasing it, as is the case with fuels like coal or natural gas, which contribute to GHG emissions. In fact, electricity production from sugarcane bagasse in Guatemala alone helps prevent the emission of around 4 million tons of CO_2e annually into the atmosphere (Salazar et al., 2023), highlighting just how significant its environmental impact can be.

In Argentina, in 2009 the facilities that allowed for the first time in the country the sale of surplus electrical energy to the national grid by a sugar mill were completed, with a 4 MW power surplus. In 2024, that figure rose to 50 MW delivered to the national grid by six sugar mills, with projects and investments in the process to keep increasing the energy delivered by both the mills that already deliver energy and those that do not yet.

Sugarcane bagasse-based electricity production also plays a crucial role in Latin American economies. Not only does it represent an opportunity for sugar mills to be self-sufficient in terms of energy, but it also means the possibility of diversifying their product portfolio. Besides creating jobs in rural areas, this activity also saves foreign exchange for the countries where this activity is developed, by avoiding the need to import coal or other sources of energy. This, in turn, also means that economies become more energy independent, making them less exposed to the risks posed by importing energy from other countries. It also helps to keep the spot price of energy more stable, benefiting both households and companies that need electricity to produce.

For decades, many sugar companies in Latin America have made important investments in bagasse-based electricity production. By doing so, they have successfully lessened their dependence on fossil fuels, contributing to having cleaner energy matrixes throughout the region. Electricity from bagasse is produced by the sugarcane agro-industries in countries such as Argentina, Brazil, Colombia, Costa Rica, the Dominican Republic, Ecuador, El Salvador, Guatemala, Mexico, Nicaragua, Panama, and Peru.

Even though electricity generated from sugarcane bagasse has many perks, it also faces several challenges. One of its main challenges is its availability. Aside from the production in Colombia and Peru, where sugarcane is harvested all year round, bagasse availability is limited to the 6-month harvest period. This means sugarcane producers need to buy other sources of energy to meet their energy contract commitments to the national matrixes. However, new technologies could enhance efficiency and biomass storage, which could increase the time that sugarcane mills are able to offer energy throughout the year.

The Guatemalan sugarcane agro-industry has invested more than US $800 million since the 1990s in bagasse-based electricity production. This investment has positioned the sector as a key player in the national energy grid, supplying up to 30% of the country's electricity demand during the harvest season (November to May). This contribution is crucial, as it complements hydropower plants—the largest generators in the grid—during the dry season when their operations are limited. The continuous efforts of the agro-industry help ensure energy stability and

sustainability, showcasing its pivotal role in Guatemala's renewable energy landscape, and making remarkable contributions to the accomplishments of some of the United Nations' Sustainable Development Goals (SDGs), such as SDG 7 (Energy) and SDG 12 (Responsible Consumption).

Besides bagasse, sugarcane trash can be used for electricity generation. The gradual elimination of sugarcane field burning and the growing advance of green harvesting have made more biomass available for energy use in boilers. Sugarcane trash, composed mainly of sugarcane leaves and stalks, represents about 20% by weight of the harvest. In the case of Tucumán (Argentina), 151 kg of dry matter per ton of sugarcane milled is the estimate of trash. Assessments have shown its good quality as fuel, similar to that of bagasse. The energy characterization considered as standard for the sugarcane trash from Tucumán has a lower calorific value of 10,495.07 kJ/kg, moisture 15%, and ash content 11.39% (Feijóo et al., 2015).

In the case of Brazil, recent data compiled in the National Energy Balance (BEN), conducted by the Energy Research Company (EPE) under the coordination of the Ministry of Mines and Energy (MME) of Brazil, show that sugarcane continues to be the leading renewable source in Brazil's energy matrix, accounting for 16.9% of the total (Empresa de Pesquisa Energética, 2024).

Sugarcane biomass-based electricity production plays a major role in advancing towards economies that depend less on fossil fuels, supporting the sustainable development of Latin America. It brings about several environmental advantages, namely: reducing emissions, sequestering carbon, and complementing other sources of renewable energy. With the right incentives, policies, and resources for regular investments, sugarcane bagasse-based electricity could reach a higher standard, driving greener economies throughout the region (Fig. 28.3).

28.4.2 Ethanol

The transport sector around the world depends almost entirely on fossil fuels. It is crucial to decarbonize this sector while internal combustion engines are still in use and the adoption of electric vehicles continues to grow. Ethanol can be produced from many raw materials, like grains, sugars, or cellulose. Today, more than 70 countries produce and use ethanol, but carbon intensity is gaining importance in all life cycle analyses. According to the European Union Renewable Energy Directive (RED II), the GHG calculations depend on the feedstock production, processing, and distribution activities. According to the RED II calculations, sugarcane ethanol has a default value of 28.6 g CO_2e/MJ, ethanol from sugar beet in the range of 22.5–50.2 g CO_2e/MJ (it depends on the type of energy used to produce), and corn ethanol has default values from 30.3 to 56.8 g CO_2e/MJ. The industry and sustainable standards are becoming increasingly stringent, making sugarcane globally one of the crops with the lowest default GHG values.

Figure 28.4 illustrates the global warming potential of biofuels in gCO_2e/MJ, a metric that quantifies GHG emissions during all phases of biofuel production and

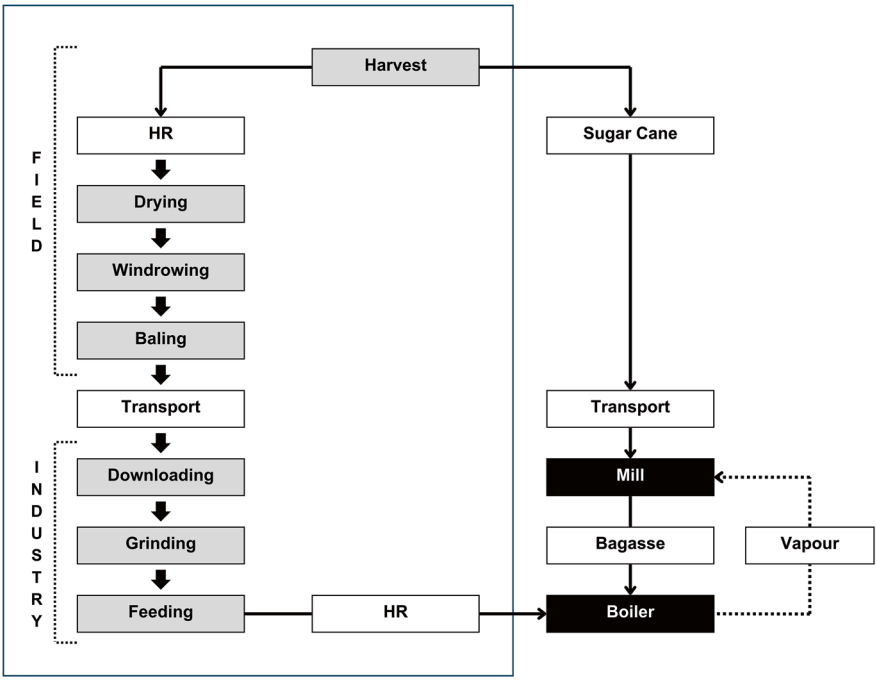

Fig. 28.3 Operational flowchart for sugarcane harvest residue (HR) collection system. The system under study is delimited by the rectangle. Source: modified from Golato et al. (2017)

use for a certain energy quantity that can be obtained from the use of that biofuel. These values are compared to the global warming potential of their fossil fuel equivalents, represented by the dashed line.

Brazil has more than four decades of producing and using ethanol in the gasoline from sugarcane. In Latin America, there are other countries that produce from this sustainable biomass, namely: Argentina, Bolivia, Colombia, Ecuador, Paraguay, Peru, and Uruguay. These countries have a blending program with gasoline. On the other hand, Costa Rica, the Dominican Republic, Guatemala, Mexico, Nicaragua, and Panama are ethanol producers, but they still do not have blending programs.

Ethanol from sugarcane in Argentina is produced in 16 distilleries, attached to sugar mills located in the northwest of the country, using molasses from the sugar production process and occasionally a percentage of direct cane juice as feedstock.

Research conducted using the Life Cycle Assessment (LCA) approach (Garolera De Nucci et al., 2017) showed a noticeable improvement with the addition of bioethanol to fossil fuel. Considering gasoline and a hypothetical case of 100% ethanol (E100) in an engine, 0.735 kg CO_2eq/MJ and 0.442 kg CO_2eq/MJ are generated with gasoline and E100, respectively. This explains that climate change impact is higher for fossil fuel than for biofuel. This demonstrates a 40% reduction in emissions, meaning that gasoline emits approximately 67% more CO_2 than bioethanol.

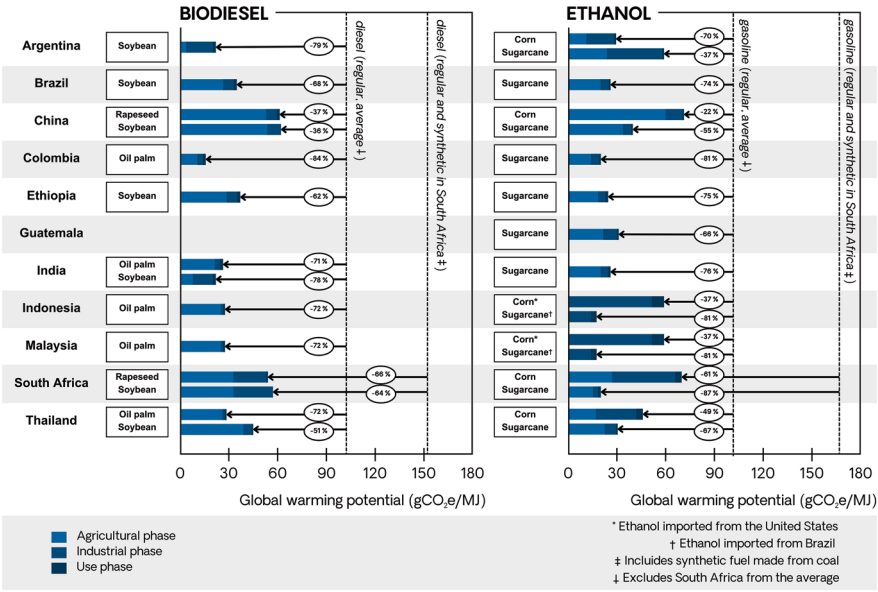

Fig. 28.4 Global warming potential of biofuels compared to fossil fuels in different countries. Source: Modified from Leal Silva et al. (2024)

This work contributes to the ongoing development of regional comparisons of the environmental profiles of gasoline-ethanol blends.

In the case of Brazil, the exploration of ethanol as a fuel began in the early twentieth century. In 1925, a Ford Model T traveled 230 km using hydrated ethyl alcohol (70% alcohol, 30% water). The motivation was primarily economic, aimed at reducing the country's dependence on imported gasoline. Over the following decades, regulations were established requiring the blending of alcohol with gasoline, such as the decrees of 1931 and 1938. However, a major turning point came in 1975 with the launch of the National Alcohol Program (Proálcool), which was developed in response to the 1973 oil crisis that severely impacted the global economy (Castro, 2017).

Proálcool was designed to create a domestic alternative to oil, relying on the sugarcane sector, which was already growing due to strong sugar exports. The program gained further traction when the first ethanol-powered vehicle was introduced by the national automotive industry in 1979. From that point on, the Brazilian government actively supported the production and consumption of ethanol as a fuel.

Ethanol offers clear advantages over fossil fuels. As a renewable biofuel, it can reduce greenhouse gas emissions by up to 90% during combustion, making it a key tool in mitigating climate change. The development of Proálcool and the broader adoption of ethanol in Brazil demonstrate how public policy can drive innovation and sustainability in the energy sector.

In 2017, Brazil introduced RenovaBio, a policy aimed at expanding biofuel use in its energy matrix. The program seeks to reduce GHG emissions, promote the

decarbonization of transportation, and align with global climate commitments made at the Paris Agreement.

A study published in *Nature Communications* highlighted the positive public health effects of ethanol use by showing a correlation between fuel choice (ethanol or gasoline) and the number of nanoparticles in São Paulo's air. Researchers found a 30% increase in the concentration of particles smaller than 50 nm in diameter when gasoline, instead of ethanol, was used in flex-fuel vehicles, indicating that ethanol use reduces nanoparticle emissions (Salvo et al., 2017).

Similarly, a 2013 study by the University of São Paulo concluded that the exclusive use of pure gasoline in Brazil's eight largest metropolitan regions would result in 1384 additional deaths and over 9000 respiratory illness cases annually, adding about R$ 430 million in healthcare costs. The same study estimated that expanding hydrated ethanol use between 2015 and 2030 could prevent more than 6000 respiratory-related deaths, corresponding to a savings of $894.8 million for the healthcare system (Ferrini, 2020). Similar findings were found for São Paulo in a later report (Ministerio de Minas e Energia, 2021).

It is evident that ethanol fuel plays a crucial role in the new global energy transition scenario. Ethanol is a quick and commercially scalable solution for reducing emissions across various modes of transportation. Public policies, such as those implemented in Brazil, are necessary to ensure the replacement of fossil fuels. Biofuels can enhance energy security and mitigate climate change. However, if not properly managed, they can also lead to biodiversity loss, water resource depletion, air and water pollution, among other impacts.

28.4.3 Other Products

There are several other products that are being produced in Latin America and that have great potential for expansion. One of them is paper produced from bagasse in Argentina, Colombia, and Peru. Yeast is another one, and cane and beet molasses are the main raw materials for its production. They provide all the sugars for yeast to develop, the energy, and some of the necessary nitrogen (Lallemand, 2001). Some of the most promising by-products are mentioned next.

Bioplastics

Sucrose, bagasse, molasses, and ethanol can be used to produce bioplastics (Aguilar et al., 2019; Aguilar Rivera, 2009). According to Suarez et al. (2023), the bioplastics industry has grown exponentially in the past years, and it is expected to triple by 2026.

Different bioplastics are produced, but bio-polyethylene presents an interesting opportunity since its fossil counterpart is one of the most used materials worldwide (Suarez et al., 2023). It has the same properties as conventional polyethylene, but it is renewable and reduces the carbon footprint. Various companies are already

marketing these products on a global scale, providing packaging for major brands (Belloli, 2010).

Lignocellulosic biomass is the basis for many biopolymers, which are available for various applications (de Resende & da Costa, 2020). Cellulose, hemicellulose, and lignin, including those from sugarcane bagasse, are some of the most currently used.

Biodegradable Packaging

There is a growing need for sustainable packaging materials at present due mainly to land and ocean pollution, especially by plastic materials, which take hundreds of years to decompose. Also, the extraction and manufacturing processes of common materials contribute to greenhouse gas emissions (Hussain et al., 2024).

Sugarcane has emerged as a promising raw material for the production of sustainable packaging, primarily through two by-products: sugarcane bagasse and bioplastics. Sugarcane bagasse can be transformed into biodegradable packaging through compression and molding processes. These packages are eco-friendly alternatives to traditional plastic, offering faster decomposition and a smaller environmental impact (Stroescu et al., 2024). Compostable packaging materials from sugarcane (and cornstarch) were first introduced in the 1990s (Hussain et al., 2024).

The use of sugarcane-based materials in packaging manufacturing is gaining relevance in sectors such as food, cosmetics, and cleaning products, as demand for more sustainable solutions grows. This innovation contributes to the circular economy by reducing plastic waste and the consumption of fossil fuels. Significant investments have been made in Argentina, Colombia, Mexico, and Peru to produce packaging with sugarcane as feedstock.

CO_2 for Carbonated Drinks

The raw material used is the CO_2 generated during the alcoholic fermentation process of molasses or honey derived from sugar production in distilleries annexed to sugar mills. During this process, the sugars present are converted into ethanol and carbon dioxide (CO_2) by the action of microorganisms, mainly yeasts. The "raw" CO_2, which is a mixture of gases containing CO_2, ethanol, N_2 and O_2, is captured and then purified through a series of processes to obtain only food-grade carbon dioxide, which is used to produce carbonated water and as an input for the food and chemical industries, among others, for various uses (Sianca, 2009).

Theoretically, for every 100 kg of ethanol produced, 95.6 kg of CO_2 are produced. Its production has a great environmental impact, as it eliminates the gases emitted into the environment, reducing GHGs by replacing the CO_2 obtained from fossil fuels. There is demand for this product in the world market (Sianca, 2009).

Biochar

The research conducted by DIECA in Costa Rica explores the conversion of sugarcane trash into biochar and its preliminary experimental impact on crop productivity. Biochar produced by pyrolysis of different "*bio-wastes*," including biomass from agro-industrial activity, has shown promise in improving soils' physicochemical properties, including structure, water retention, and cation exchange capacity

(Kameyama et al., 2017; MEFT/GIZ, 2020; Snohomish Conservation District, 2018). The massive use of biochar in agriculture would permit a significant reduction in the amounts of chemical fertilizers applied and favor carbon sequestration in soils contributing to Climate Change mitigation (FAO, 2019; MEFT/GIZ, 2020; Moyer et al., 2020). Initial results indicate that biochar significantly increases carbon content and organic matter in acidic soils (mainly Ultisols), improving their pH and nutrient retention capacity (Núñez-Chacón, 2023).

28.5 Future Pathway

As has been shown here, there are many ways in which sugarcane has contributed to the bioeconomy, and there has also been progress in circularity in Latin American countries, and there are abundant possibilities for the future. Nonetheless, as not all good practices are the norm, there is immense potential in their widespread adoption. In this section, lessons will be shared and ways that need to be addressed for the potential to be reached.

28.5.1 Environmental Impact and Circularity

There are four main environmental impacts that are of concern in the sugarcane growing areas, namely: water use, pre-harvest burning, agrochemical use, and deforestation. They have been a source of conflict and accusations by several stakeholders. If the sugarcane agro-industry is to be a key player in a circular bioeconomy, those concerns need to be addressed. Fortunately, there has been progress in several countries and regions around those concerns, and their lessons should be used as a basis for widespread adoption of good practices.

Investment is necessary. From research to capacity building to the purchase of equipment, funding is needed. Sugarcane growers and manufacturing companies have funded most of what has been done in Latin America, but available funding and fluctuations in the international prices of sugar and ethanol, especially, limit investment in some years (of low prices). Governments can support certain programs for small farmers and mitigate the potential impact of certain changes in processes. This was the case with the mechanization of harvesting in the state of São Paulo, Brazil, where thousands of cane cutters were going to lose their jobs.

Other elements include:

- Measuring and monitoring are key.
- There are technical limitations. For example, a mechanized harvest that is needed to avoid pre-harvest burning cannot be carried out everywhere.
- External factors need to be considered: for example, cane burning by third parties.
- Research is critical and investment from private and public sources should be provided, as well as collaboration between research centers in the continent.

- Capacity building (training) and change management are necessary.

Besides the four main environmental concerns listed above, soil degradation should also be tackled. Aspects that need to be considered are soil erosion (through rainfall), soil fertility, and physical properties. Again, there is progress in Latin America with a shift to the concept of "living soil" (*suelo vivo*) being adopted by three companies in Guatemala (Pantaleon, Magdalena, and Santa Ana). In this regard, there is also potential in looking at agricultural soils as a carbon sink, subject to carbon markets. It is necessary to continue advancing the development and application of biofertilizers, taking advantage of all available technological resources.

To address all potential environmental impacts from sugarcane and all its products and by-products, the Life Cycle Assessment (LCA) is the ideal tool to assess the sustainability of a process, product, or activity. It was used in Tucumán, Argentina, where the bioethanol environmental profile was determined by analyzing the potential environmental impacts (global warming, biodiversity loss, water scarcity, fossil resource depletion, eutrophication, among others) associated with the entire production process. This analysis accounted for resource consumption and emissions generated throughout the life cycle, from the agricultural to the industrial stage, using 1 MJ of anhydrous ethanol as the functional unit and employing the ReCiPe Midpoint impact assessment method (Garolera De Nucci, 2016; Garolera de Nucci et al., 2019).

28.5.2 Potential for New Products from Sugarcane

The experience thus far in Latin America has been that using residues and by-products from sugarcane processing can be an important part of economic sustainability. The environmental benefits were probably "lucky side effects" at the beginning, but critically important, nonetheless. The potential to use all parts of sugarcane has been pinpointed for decades, and developed countries have taken advantage of it, thus buying raw sugar and molasses, for example, as raw materials. Figure 28.2 shows the potential use of the main products and by-products of sugarcane. The use of each of the products has further options. Paturau (1982), for example, long ago indicated that through three processes (fermentation, synthesis, and degradation), sucrose itself could derive into 33 products. Not only could Latin American countries produce many of the existing products in developed countries themselves, but they could produce higher value products from the materials that are not exported (i.e., bagasse, residues in the field, molasses and vinasse). According to the experience in the region, what is needed to advance is:

- Funding, especially for initial investment.
- Large-scale production
- Human talent, including specialized labor
- Research and development

28.6 Conclusion

Sugarcane is a strategic crop for a circular bioeconomy in Latin America. The different examples and cases illustrated the diversity of uses of this plant and all its derivatives, many of them replacing what are at present fossil fuel-based materials. Because of the history of sugarcane cultivation (and nearly all crops), there are concerns about the sustainability and circularity of its production system. Progress in that regard was also shown through examples in several countries. The cases, although not explained in detail, showed that vision, investment, and capacity building from (private) producers have been key to progress. However, the role of governments through legislation, policies, and programs has been essential for the advancement of some areas, such as the use of ethanol to replace gasoline. Even though the focus of the chapter was on environmental, in many cases the main motivation for growers and companies was economic sustainability. The environmental benefits, nonetheless, were as important. This chapter did not look at the social aspects, though some could be inferred, especially through reducing environmental impacts. Possibly the main one is the improvement of water quality in some rivers by tackling pollution from mill wastewater as well as from solid cane residues.

Several elements are needed to reach the full potential of sugarcane in a circular bioeconomy. For companies to be willing to invest, they need legal certainty, long-term contracts, and incentives. Clear regulations and long-term stability are needed from governments. Research and development are also key. Lastly, the growers and companies that process sugarcane need to be aware of their surroundings, including neighboring communities, the watersheds in which they operate, and even the global stage. This sector has the potential to lead the way for other crops and to be a proactive member of Latin America for a sustainable future.

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