Routledge Studies in Ecological Economics

THE CIRCULAR BIOECONOMY

INSTITUTIONAL AND PRODUCTION PERSPECTIVES

Edited by
Małgorzata Pink and Agnieszka Józefowska

ROUTLEDGE

The Circular Bioeconomy

Founded on distinct principles to the fossil fuel-based, linear economy, the sustainable, circular bioeconomy requires different social values and institutions and a better understanding of the complexity of the production process. A circular bioeconomy provides a framework for using renewable natural capital to manage land, biodiversity, food, and other industries, with the aim of improving social well-being and environmental safety.

The contributors to this book analyse the evolution of the economic system towards the circular economy and bioeconomy and its place in the paradigm of sustainable development. They look at institutions and their importance for the bioeconomy and examine the question of the behaviour of market entities – enterprises and consumers – as well as the meaning of social and environmental responsibility for these entities. They also discuss the issues of the product itself: the process of creation, production, processing and the quality of the product, including its environmental impact throughout its life cycle. The authors also refer to the potential pitfalls and threats related to the implementation of the bioeconomy in both socio-economic and environmental contexts. Individual processes and phenomena are illustrated with case studies and the authors' own research.

The book deliberately fosters an interdisciplinary approach founded on cooperation between economists, management specialists, agronomists, biotechnologists, chemists and soil scientists, who together underline the complexity and importance of the interdependence of the economy, society and the natural environment.

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Part I

Socio-economic contexts of the circular bioeconomy

Idea, institutions and stakeholders

1 Evolution of the economic system

From a fossil-based economy to the circular bioeconomy

Beata Pater, Jakub Piecuch, Małgorzata Pink, Radka Redlichová and Vojtěch Tamáš

1.1 Introduction

Thinking in economic categories is an innate characteristic of the human species, because the very idea of community is founded on exchange, cooperation and the sharing of limited resources. According to a commonly known and accepted definition of economics, shaped by the neoclassical economists Lionel Robbins and Alfred Marshall, it can be defined as the science of allocating limited goods to satisfy unlimited needs. Thus, when seeking to maximise utility, economics always considers both the returns (benefits) and the costs necessary to achieve these returns, and we seek to maximise their ratio, i.e. to behave efficiently. However, the desired outputs and their value, as well as the value of inputs, is subjective. Individuals and societies may therefore have different, or often conflicting, interests. Such contradictions can then result in conflicts. What is necessary for one generation, another may consider unnecessary or even harmful. It is this "temporal conflict" that contemporary society is now facing. There is a growing awareness that the time of resource depletion and planetary boundaries is approaching and that current practices are no longer sustainable. If we want to preserve the well-being of the next generation, it is essential to change the paradigm of our contemporary attitudes and pay attention to long-term sustainability. One approach that offers a way of responding to the current situation is the circular (bio)economy. Its aim is to use resources that are renewable and not to waste non-renewable resources, but to include them in the use loop. This change can be slow and will require a lot of effort but the journey can be the destination, with the goal being a more sustainable life for ourselves and our descendants.

1.2 Has economic theory prepared us for the climate crisis?

The development of every civilisation depends on the ability to manage available resources, which is related to the ability to sustain the population, ensure security and foster societal progress. Economic relations have developed naturally in response to the evolution of society and its needs. From

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history, it is known that civilisations that failed to fulfil these requirements eventually fall into decline. Together with the changes in society, there have been gradual changes in approaches to economic thinking in response to its current needs.

Significant economic ideas can be found in Ancient Greek philosophy. For Aristotle, 'oikonomia' meant running a household in order to satisfy the needs of household members. That which cannot be produced by oneself can be acquired through exchange and that was a commendable activity, in contrast to 'chrematistike', which served to gain wealth and increase money but not to satisfy needs. Aristotle considered such an activity to be shameful and incompatible with nature.[1] In the centuries that followed, economic problems were addressed by philosophers, clergymen and political theorists and economic issues were linked to other areas of humanist and social reflection. This changed with the Industrial Revolution, which established economics as a science in its own right. Economic growth quickly became the key problem of economic science, imposing a linear way of thinking about material progress. The foundation of most of the theories was to understand how to achieve long-term economic growth and how to increase the productive capabilities and productivity of the economy and the standard of living of the population. The last 250 years have been a success in this respect, although the price of economic growth has been paid in the form of external environmental costs (Figure 1.1).

A rapid increase in the concentration of greenhouse gases in the atmosphere, and an increase in average temperatures, as well as a dramatic decline in biodiversity, an increase in the amount of foreign substances in the environment, land system change and soil degradation, and the destruction of

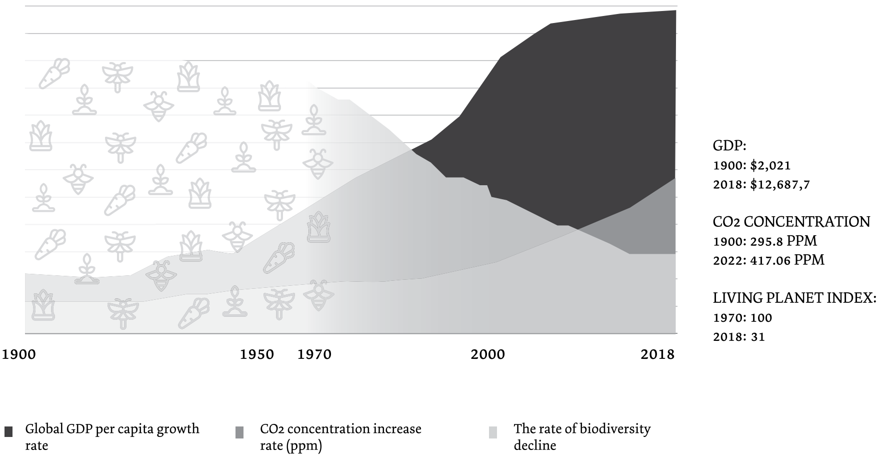


Figure 1.1 Environmental cost of economic growth.

Source: own elaboration.[2]

biogeochemical flows (nitrogen and phosphorus flows) are just some of the planetary boundaries that have been exceeded to an extent that endangers the life of the planet.[3] Contrary to appearances, economic theorists have understood the potentially dangerous effects of excessive exploitation of natural capital almost from the very beginning.

Modern economics date back to the period just before the Industrial Revolution. Classical Political Economy, with the work of the Scottish economist Adam Smith and his *An Inquiry into the Nature and Causes of the Wealth of Nations* (1776), marks the beginning of the economic era. The emergence of industrial capitalism left little room for reflection on environmental issues. Typical for those times was the advocacy of principles of liberal capitalism, emphasising the natural order, freedom and the invisible hand of the market, where the principle of 'laissez-faire', meaning minimal government intervention in market operations, was an official modus operandi. The classical economists saw production as a lever for progress and a guarantee of prosperity. Technological progress and the mastery of man's ability to generate energy gave rise to optimism and strengthened man's position as steward of the natural world. David Ricardo, wrote: '... *air and water, or for any other of the gifts of nature which exist in boundless quantity*',[4] establishing a fairly relaxed approach towards ecosystem resources. The exploitation of the environment and the destruction of ecosystems were not present in the public consciousness, which is understandable since the population had only just passed the 1 billion mark in around 1800.[5] Despite its expansion, humankind was still a relatively harmless species. The optimism that characterised the long-term vision at the beginnings of the classical age evaporates with first crises of capitalism. The theory of Robert Malthus is based on the idea of potential resource scarcity for an exponentially growing population. Many economists have deemed Malthus's model to be ineffective due to the absence of technology,[6] which contributes to the overall efficiency of agriculture and thereby influences food supply. Malthus presumed, however, that there are natural limits to agricultural production,[7] and therefore his theory can be read as the first alarm bell for future generations, particularly regarding the issues of sustainable population growth and resource depletion.

Another representative of the classical period whose theory foreshadowed contemporary environmental problems was Karl Marx. Although he was criticised for neglecting issues of exploitation of nature, its role in value creation or the existence of boundaries of nature, according to J.B. Foster, he was actually a precursor for sustainability in predicting a metabolic rift.[8] Karl Marx, being greatly influenced by the work of Justus von Liebig, an agricultural chemist who dealt with the role of fertilising soil with nitrogen-rich guano, understood the relationship between man and nature to be a metabolic one. Goods consumed by humans should return to nature in a literal sense, in the form of nutrient-rich faeces, and also in a social, communal context, in the form of materials that can be consumed by the earth to maintain sustainability. In adopting this approach, Marx can be considered a forerunner of the circular (bio)economy. In capitalism, this does not happen; capitalism disturbs and destroys this metabolic relationship, alienating man from nature, and from other members of society and the effects of his own work. It functions in structures that turn material energy into capital, which has a different character and does not participate in this metabolic exchange. In this way, the metabolic rift is created and deepens (Figure 1.2).

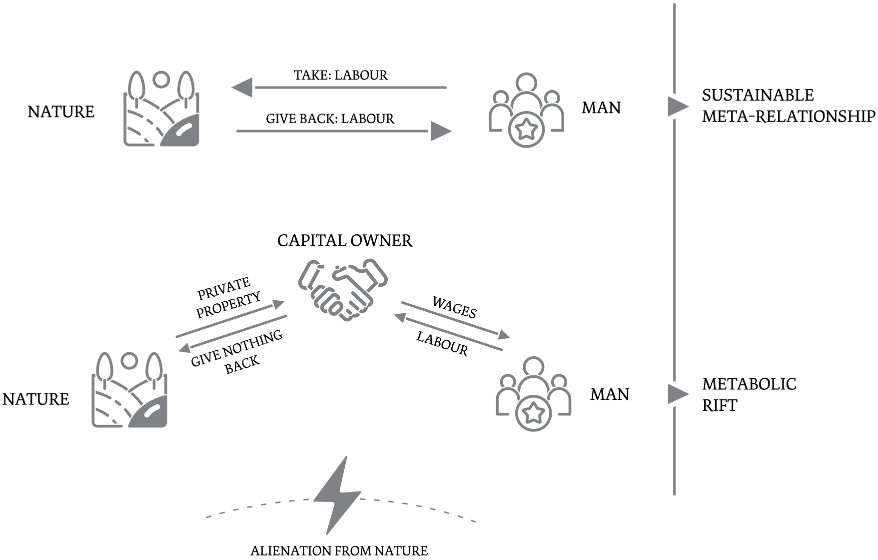


Figure 1.2 Metabolic rift caused by breaking the sustainable relationship between man and nature.

Source: own elaboration.

Nearly 40 years after Marx's death, in 1920, Arthur Pigou published *The Economics of Welfare*, a book in which he defined positive and negative externalities. Externalities can be defined as costs or benefits incurred by third parties who are not parties to a market transaction. In this context third parties can be understood as both individuals and entire social groups. Pigou argued that negative externalities should be offset by a tax, while positive externalities should be offset by a subsidy. The issue of externalities entered economics as a potential cause of market failure and laid the groundwork for the concept of environmental taxation. Pigou recognised that externalities are of great importance in the context of the efficiency of resource allocation and the effects of their division. Externalities cause changes in the environment, which have a negative impact on the capabilities of economic entities to produce and consume. Neoclassical economists only took technological costs into consideration as direct external costs, which are not compensated by market transactions. Under conditions of perfect competition, economic entities tend towards the optimum allocation of resources in the sense of the Pareto optimum. The occurrence of external costs is thus linked to imperfection of the market and causes suboptimal allocation, which can be prevented by the internalisation of external costs, i.e. including the costs of environmental protection in the costs of production of goods and services. Marketisation helps counteract environmental pollution and can serve to remove the raw material barrier to growth thanks to price increases and greater substitution. Internalisation is based on Pigou's concept of optimal tax and the Coase theorem, and is applied in practice as the *polluter pays* principle. Pigou's tax, however, excludes the payment of compensation to individuals suffering damages. Although victims have no influence on the amount of pollution, they can influence the amount of losses incurred. This is why Ronald Henry Coase suggested that victims be taxed as well, so that they take preventive measures.[9,10]

Neoclassical economics connects the impact of externalities and the process of their internalisation with improving the functioning of the market, also by limiting the availability of public environmental goods. This point of view is criticised by Keynesians, who believe that the neoclassical understanding of the microeconomic calculus of optimisation and market forces is not the right approach to solving the problem of pollution and protection of the environment. The State should also regulate the rate of exploitation of natural resources. According to Keynesian economics, the most appropriate tool is the political criterion of intergenerational ecological fairness; in other words, politically conditioned consent to maintain an appropriate quality of the environment for future generations,[11] in accordance with the principle of eco-development and the concept of sustainable development, which emerged in the late 1980s.[12]

1.3 Unveiling the essence: exploring the conceptual landscape of the bioeconomy

In the first half of the 20th century, environmental pollution was not perceived as a serious problem for the economy and society, although the constantly increasing pressure on the natural environment forced us to rationalise the use of natural resources. This was influenced by the civilisation crisis, and especially in a social and economic context, by changes in the way we perceive reality and ethical considerations. A process of changes in social awareness and science was set in motion as a result.

The concept of eco-development and then sustainable development began to be discussed after 1980. The reason for the considerations was a report published in 1969 by the UN Secretary-General U Thant entitled *Man and his environment*, which contributed to organising the UN global conference on the *Human Environment* in Stockholm in 1972. This event mobilised the participating countries to draw up an inventory of the state of the natural environment and indicated the need to make international arrangements regarding environmental protection and rationalisation of economic activities. The concept of eco-development was then defined as conducting business activities in a way that would not cause irreversible changes in nature. Broader discussions on the concept of sustainable development began with the publication of the report of the World Commission on Environment and Development, chaired by Gro Brundtland, then Prime Minister of Norway, entitled *Our common future*. In addition to the most well-known definition of sustainable development, according to which it is development that meets the needs of the present without depriving future generations of such opportunities,[13] long-term strategies were proposed to enable the implementation of this concept in socio-economic life by the year 2000. Sustainable development is included in the Maastricht Treaty.[14]

The concept of sustainable development arises by adopting a critical approach to the theories of economic growth and prosperity that dominate in economics, especially in its neoclassical form. An attempt was made to create a new moral and philosophical order through criticism of existing production and consumption trends, as well as criticism of macroeconomic and sectoral policies. A model of socio-economic development was proposed, which integrates political, economic and social activities, while maintaining natural balance and the sustainability of basic natural processes, in order to guarantee the potential to meet the basic needs of individual communities or citizens of both current and future generations. Additionally, the concept of zero growth, which was supposedly necessary as a result of the depletion of natural resources, was rejected. Self-sustaining development is intended to prevent this through the development of low-waste and no-waste technologies and recycling.

The scientific roots of the bioeconomy can be linked to the theory and practice of sustainable development due to the role of the natural environment and the use of its resources in this concept. In 1977, Nicolas Georgescu-Roegen, an American economist of Romanian origin, pointed out that the study of economic phenomena and processes should take into account the biophysical and social context of processes of production, exchange and consumption, pointing to the biological limitations of economic growth. He believed that land resources should also be available and usable by future generations. He called this approach the bioeconomy.[15] However, it was only in the second decade of the 21st century that the concept of the bioeconomy began to appear more and more often in theory, strategic planning and the economy of countries of the European Union (EU). It covers the potential of primary production in fisheries and the coastal economy, the agriculture and forestry sectors, as well as the management of biomass, including that derived from waste, and the production of renewable energy based on biomass and biotechnology. This area of the EU economy is now becoming the foundation of sustainable economic growth. In its member states, in terms of annual turnover, the bioeconomy is worth approximately EUR 2.3 trillion and employs approximately 18 million people.[16]

The bioeconomy can be viewed in two ways: from a general standpoint – as a new analytical concept in the planning of economic activity and the interdisciplinary planning and financing of scientific research; and also as a sector of the modern economy which uses biological resources in economic processes

– that is, living organisms, bioprocesses and biotechnologies – to produce new goods and services that go beyond the food economy. The concept of the creation and development of the bioeconomy results from the need to ensure food security for the growing world population and the need to seek rational, economical management of non-renewable energy resources, as well as from the need to use materials and raw materials through proper waste management and recycling processes. Finding a way to transition from an economy based on fossil fuels to an economy which uses renewable energy sources on a larger scale and where development is based on scientific achievements and bio-innovations, is the basic premise of the bioeconomy.

The concept of the bioeconomy, which is also sometimes referred to in publications as the bio-economy, or the bio-based economy, can be understood as an economy that is based on goods, materials, chemical products and energy produced from biological resources.[17]

According to Juan Enriquez and Rodrigo Martinez, who are considered to have proposed the first definition of the bioeconomy, it means economic activity that is based on scientific research and implementation, focusing on understanding mechanisms and processes at the genetic (molecular) level, with a view to implementation and application in industrial processes.[18] In the following years, the definition was expanded upon or narrowed down, emphasising further aspects of the bioeconomy. In 2006, the European Commission's Directorate-General for Science defined the bioeconomy as all production systems that use biochemical and biophysical processes, including life sciences and the related technologies necessary for production. It is also the application of biotechnology in agriculture and industry, as well as biorefineries, bioenergy, and biochemicals that are an integral part of the bioeconomy. This term also covers innovative forms of use of land and sea, including those improving the functioning of the ecosystem and other public goods and the use of materials currently considered to be waste.[19]

In turn, the OECD, in its report entitled *The Bioeconomy to 2030. Designing a Policy Agenda*, defined the bioeconomy as activity involving the use of biotechnology, bioprocesses and bioproducts to produce goods and services. The report examines the development of the bioeconomy thanks to biotechnology in three sectors (industry, healthcare and agriculture) over the next two decades, up to 2030. According to the OECD, biotechnology is to be the impetus for economic growth. This growth depends on three elements: the use of advanced knowledge of genes and cellular processes to develop new products; the use of renewable biomass and bioprocesses to support sustainable production; and the integration of knowledge of biotechnology for use in multiple sectors. The use of biotechnology significantly reduces emissions, which means that economic growth does not have to be associated with the environmental degradation caused by increased emissions.[20]

The bioeconomy is therefore a method of management whose task is to find solutions to the environmental crisis without slowing down the economy. The bioeconomy focuses specifically on ecosystem products and services, based on the assumption that this approach will be more sustainable than the use of fossil fuels. As part of the green economy, at the Earth Summit in Rio de Janeiro in 2012, the development of a post-fossil bioeconomy was proposed, supported by the European Union, the United States and Brazil. This approach relies heavily on the use of biomass, both as a fuel and as a raw material, to produce a wide range of products, including chemicals and plastics. Production is possible thanks to the use of many technologies, such as genetic engineering, nanotechnology and synthetic biology.[21]

In 2012, the European Commission's *Innovating for Sustainable Growth: A Bioeconomy for Europe*[22] presented a coherent, cross-disciplinary and cross-sectoral approach to the increased and more sustainable use of renewable resources in the European economy. This approach was aimed at creating an innovative economy that protects biodiversity and the environment and, at the same time, reconciles sustainable agriculture, food security and the use of renewable resources in industry. The need to invest EU, national and private funds in research, innovation, knowledge and skills related to the bioeconomy was emphasised. The need to develop markets and competitiveness in sectors related to the bioeconomy by balancing the increase in primary production and the transformation of waste streams into products with added value was also emphasised, which requires improving production and improving the efficiency of resource use.

In 2017, after the conference in Utrecht, the European Bioeconomy Stakeholders Manifesto was published.[23] At the Bioeconomy Stakeholders Conference in 2016, it was concluded that the bioeconomy should be combined with the effective management of raw materials, and that biomass should be managed in such a way as to provide the greatest possible added value. The reuse of raw materials is an important aspect of their management.

In 2018,[24] the bioeconomy strategy from 2012 was refreshed. This strategy contributes to industrial innovation, to circular economy and clean energy strategies and, above all, to the European Green Deal. The document highlights the importance of a sustainable and circular bioeconomy in achieving its goals, namely: ensuring food and nutritional security; managing natural resources in a sustainable way; reducing dependence on non-renewable and unsustainable resources; limiting and adapting to climate change; and strengthening Europe's competitiveness and creating jobs. In the context of the EU 2012/2018 bioeconomy strategy, it can be defined as the sustainable production of biomass and their processing into medicines and supplements, food, feed and industrial goods (bio-based materials and chemicals fuels and energy). The bioeconomy covers all sectors and systems using biological resources (animals, plants, microorganisms and the biomass produced by them, including biological waste), their functions and principles. This includes: terrestrial and marine ecosystems and services provided by them; all primary production sectors that use and produce biological resources (agriculture, forestry, fisheries and aquaculture); and all the economic and industrial sectors that use biological resources and processes for the production of food, feed and industrial goods. This definition will be the interpretation used for the purposes of this publication.

Actions for the development of a circular bioeconomy involve the optimal use of resources and reducing the impact of the product life cycle on the natural environment. The European Commission's 2020 communication A new Circular Economy Action Plan[25] states that circularity is an important part of the broader industrial transformation towards climate neutrality and long-term competitiveness. It can deliver significant material savings across value chains and production processes, generate additional value and unlock economic opportunities. According to the document, the circular economy can significantly reduce the negative impact of resource extraction and use on the environment and contribute to restoring biodiversity and natural capital in Europe. Biological resources are a key contributor to the EU economy and will play an even more important role in the future. It was stressed that the Commission will strive to ensure the sustainability of renewable bio-based materials, including through actions in line with the Bioeconomy Strategy and Action Plan.

In 2022, a report on progress in implementing the bioeconomy strategy was published. The report highlights the importance of the bioeconomy in the new political environment described in the European Green Deal. As the fossil fuel economy has already reached its limits, it is necessary to move towards a new social and economic model based on the sustainable use of biological resources in a closed loop. A bioeconomy that integrates different policies and has the potential to improve policy coherence allows countries and regions to design transition pathways according to their capabilities (Table 1.1).[26]

Older definitions place a clearer emphasis on the biotechnology context, as does the White House definition. A more modern view of the bioeconomy takes the aspects of sustainable production and the ecological environment into account. The circular (bio)economy[27] (see Figure 1.3) is becoming an economic paradigm, having previously been just one of the tools of the "greener economy" understood in the broader sense.

In this paradigm, the bioeconomy is an immanent pillar of the circular economy. Together with some other innovative phenomena in the social economy, it originates from a new set of values and goals. The assumptions and goals of the bioeconomy are closely related to Kate Raworth's concept of the Doughnut Economy. This model is also based on the assumption that the interests of humans and Planet Earth are to be reconciled, with care for development, prosperity and equality in society, and a commitment to the protection of natural ecosystems, biodiversity and resources. The Doughnut Economy model assumes that, with little or even no economic growth, redistribution of the wealth generated will become more important. There are seven rules in the doughnut economics model (Figure 1.4).

Economic development must have two limits defined by an inner ring (social foundation) and an outer ring (ecological limit). Inside, there are social phenomena in which there are undesirable deficiencies; outside the planetary boundaries that have been overshot. The economic goal is to remain within the established framework and eliminate overshoots and shortages through a regenerative and distributive economy (see Figure 1.5).

Table 1.1 Overview of approaches and definitions of the bioeconomy 1977–2022

Year	*Author*	*How to understand the concept of the bioeconomy*
1977	Georgescu-Roegen	The use of land resources with the prospect of preservation and use by future generations, as there are biological limitations to economic growth.
1998	Enriquez Martinez	Economic activity that is based on scientific research and implementation, focusing on understanding mechanisms and processes at the genetic (molecular) level, with a view to implementation and application in industrial processes
2006	European Commission-General for Research and Innovation	Every production system that uses biochemical and biophysical processes, including life sciences and related technologies necessary for production. It is also the application of biotechnology in agriculture and industry, as well as in biorefineries, bioenergy, and biochemicals that are an integral part of the bioeconomy. This term also includes innovative forms of use of land and sea, including those improving the functioning of the ecosystem and other public goods, as well as the use of materials currently considered to be waste.
2009	OECD	Activities involving the use of biotechnology, bioprocesses and bioproducts to produce goods and services.
2012	United Nations – Earth Summit in Rio de Janeiro	The bioeconomy focuses specifically on ecosystem products and services, based on the assumption that this approach will be more sustainable than the use of fossil fuels. The use of biomass, both as a fuel and as a raw material, to produce a wide range of products, including chemicals and plastics. Production is possible thanks to the use of many technologies, such as genetic engineering, nanotechnology and synthetic biology.
2012	European Commission	The economy of using biological resources of land or marine origin, as well as those derived from waste, including food waste, as inputs to industry and energy generation; also includes the use of bio-based processes in environmentally friendly industries.
2012	White House (USA)	Based on the application of research and innovation in the life sciences to drive economic activity and generate public profits.

(*Continued*)

Table 1.1 (Continued)

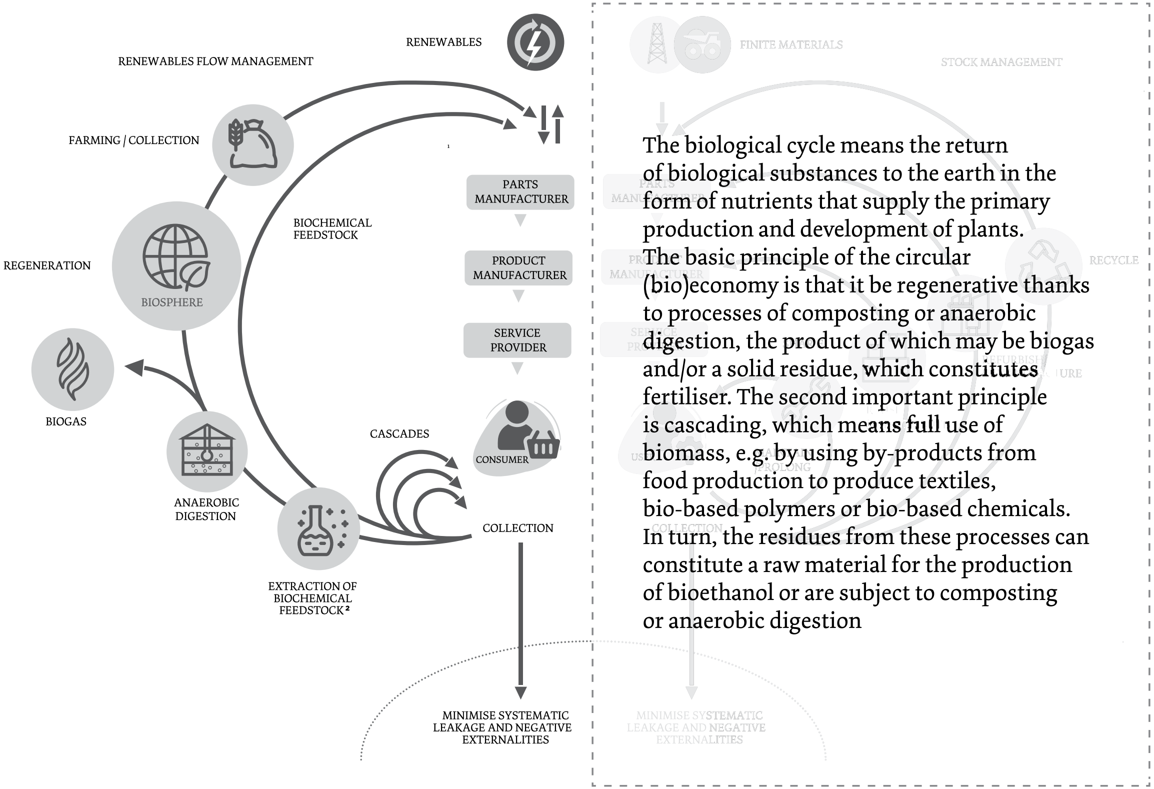
Year	*Author*	*How to understand the concept of the bioeconomy*
2018	Iris Lewandowski	Sustainable and innovative use of biomass and biological knowledge to provide food, feed, industrial products, bioenergy and ecological services
2018	European Commission	The importance of a sustainable and circular bioeconomy was highlighted to ensure food and nutrition security, manage natural resources sustainably, reduce dependence on non-renewable and unsustainable resources, limit and adapt to climate change and strengthen Europe's competitiveness and create jobs.
2022	European Commission	The importance of the bioeconomy in the new political environment described in the European Green Deal is recognised. As the fossil fuel economy has already reached its limits, it is necessary to move towards a new social and economic model based on the sustainable use of biological resources in a closed loop. A bioeconomy that integrates different policies and has the potential to improve policy coherence allows countries and regions to design transition pathways according to their capabilities.

Source: own elaboration.

Replacing conventional production with a sustainable, circular bioeconomy will directly contribute to reducing overshooting of all environmental ceilings and eliminating some deficiencies inside of the model, including the aspects of food, water, energy and housing. However, it should be emphasised that this is conditional upon a sustainable approach to primary production, the elimination of or significant reduction in the supply of synthetic fertilisers and pesticides, and full use of the potential of biomass by including it in the circular cycle. The production, use and processing of biomass can provide a solution to environmental and social problems while maintaining material quality of life, but, in the absence of the appropriate legal and institutional framework, it can involve significant risks and a degree of exploitation which is indistinguishable from the predatory economy that has led to the ecological crisis.

1.4 Exploring potential risks in the bioeconomy: anticipating challenges and enhancing resilience

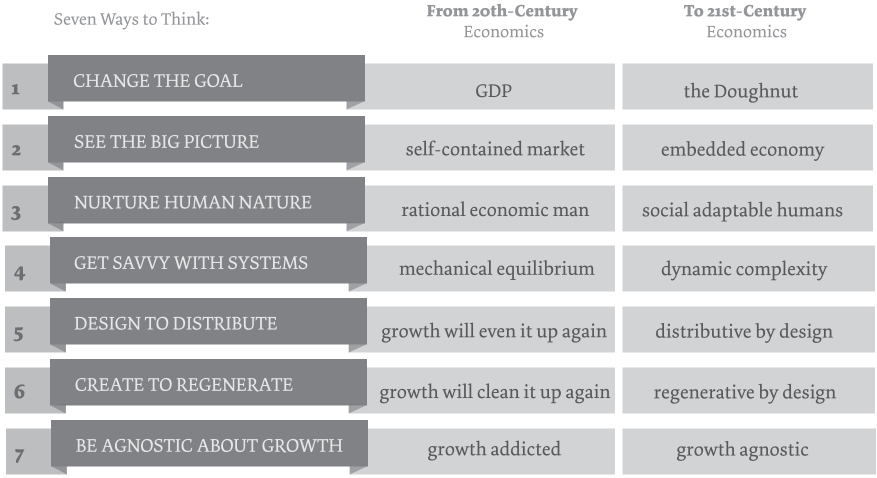
In addition to the benefits that the application of the principles of circular (bio)economy offer, it is also necessary to be aware of the possible shortcomings or failures that may occur in this context. Such shortcomings or failures



The biological cycle means the return of biological substances to the earth in the form of nutrients that supply the primary production and development of plants. The basic principle of the circular (bio)economy is that it be regenerative thanks to processes of composting or anaerobic digestion, the product of which may be biogas and/or a solid residue, which constitutes fertiliser. The second important principle is cascading, which means full use of biomass, e.g. by using by-products from food production to produce textiles, bio-based polymers or bio-based chemicals. In turn, the residues from these processes can constitute a raw material for the production of bioethanol or are subject to composting or anaerobic digestion

Figure 1.3 Circular (bio)economy as one of the pillars of the circular economy.

Source: Adapted from Ellen MacArthur Foundation, Circular economy systems diagram (February 2019) www.ellenmacarthurfoundation.org. Drawing based on Braungart & McDonough, Cradle to Cradle (C2C). Credits: Copyright © Ellen MacArthur Foundation (2024), www.ellenmacarthurfoundation.org.



Seven Ways to Think:		**From 20th-Century** Economics	**To 21st-Century** Economics
1	CHANGE THE GOAL	GDP	the Doughnut
2	SEE THE BIG PICTURE	self-contained market	embedded economy
3	NURTURE HUMAN NATURE	rational economic man	social adaptable humans
4	GET SAVVY WITH SYSTEMS	mechanical equilibrium	dynamic complexity
5	DESIGN TO DISTRIBUTE	growth will even it up again	distributive by design
6	CREATE TO REGENERATE	growth will clean it up again	regenerative by design
7	BE AGNOSTIC ABOUT GROWTH	growth addicted	growth agnostic

Figure 1.4 Seven ways to think like a 21st century economist.

Adapted from Raworth, K. (2017) *Doughnut Economics: seven ways to think like a 21st century economist*. London: Penguin Random House.

that are of global relevance include, for example, land grabbing, displacement, or various inequalities (economic, social and resource distribution, etc.). To understand the sense of the circular (bio)economy and achieve the best results, it is necessary to understand these negative impacts and to be able to work with them when trying to change the economic paradigm from a linear to a circular paradigm. The risks and threats arising from the bioeconomy are related both the environmental and biological context (discussed in greater detail in Chapter 8) and the socio-economic context (Table 1.2).

The process of cross-border acquisition of agricultural land rights accelerated in the first decade of the 21st century. In the first years of the 21st century, Asian countries invested in cross-border land acquisition. These included: Malaysia, Singapore, China, India, Hong Kong and Saudi Arabia. This process also occurred to a large extent in Anglo-Saxon countries (the USA and the UK) and in Europe (the Netherlands and Germany). The main reason for the transborder takeover of agricultural land is the increased demand for food and bio-based energy raw materials. Land grabbing mainly affects poorer countries and is concentrated in the southern hemisphere (see Table 1.3).

Land grabbing strictly concerns biomass production. Although it is most commonly used in the poorer countries of the south, it also applies to poorer countries in Europe and the EU. In the EU, it is most common in Romania, Bulgaria, Lithuania and Hungary, although the scale of this practice within the EU is much more limited. In any case, land-grabbing practices pose a threat to sustainable development, generating the following risks:

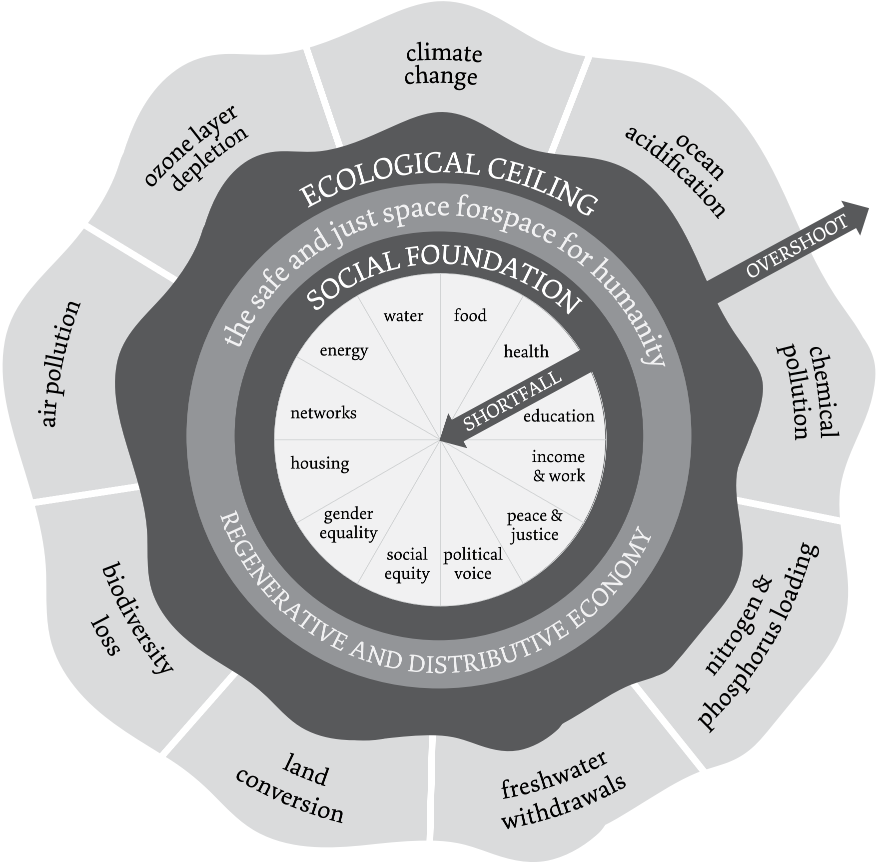


Figure 1.5 Social and planetary boundaries.

Source: Adapted from *The Doughnut of social and planetary boundaries* Kate Raworth and Christian Guthier. CC-BY-SA 4.0. Raworth, K. 2017, *Doughnut Economics: seven ways to think like a 21st century economist*. London: Penguin Random House.

- Threat to food security.
- Environmental threat, including deforestation, the destruction of ecosystems, the strengthening of monocultures in agriculture and massive use of synthetic fertilisers and strong pesticides, as well as the over-exploitation and/or pollution of water resources.
- Collapse of small and family farms and related negative changes in the labour market in rural areas
- Disregard for property rights and land use, which may pose a threat to vulnerable groups of the population and lead to the degradation of local communities.
- Increase in land prices and limited or impossible access to agricultural land for local farmers.[29,30]

Table 1.2 Examples of socio-economic threats related to the bioeconomy

Possible threat	*Examples*
Land grabbing	Acquisition of ownership or lease of large areas of agricultural land by entities from other countries (cross-border factor) for the production of food, feed and biofuels
Displacement	• The situation where people are forced to leave their place of habitual residence, for example due to • the large-scale cultivation of biomass, • economic reasons, • ethnic origin
Unequal distribution	• differing soil quality, • limited access to agricultural land, • loss of communal land, • marginalisation of some groups in terms of their needs or economic / political possibilities • unequal access to knowledge and innovations in the bioeconomy

Source: Own elaboration.

To address the problems associated with land grabbing within the framework of the bioeconomy and circular economy, it is essential to use transparent and participatory processes that consider the interests of local communities. International cooperation and regulation should aim to reduce unethical practices and protect the rights of local communities. The issue of land grabbing in the context of the circular (bio)economy often crosses borders and has a global impact. Rich countries invest in developing regions where they have easier access to cheap resources and labour. This can lead to a loss of livelihoods and cultural identity for local communities who are displaced from their traditional territories. Overall, the combination of land grabbing with the circular (bio)economy presents a complex challenge for global sustainable development. Finding a balance between the use of natural resources and a commitment to environmental protection and social justice is crucial for the future of sustainable land management.

One of the consequences of land grabbing and excessive biomass extraction is displacement. Up to 2020, land deals in Cambodia, Ethiopia, Liberia, and Peru have affected more than one million people.[31] The system of growing crops over large areas has contributed to the continuous displacement of small-scale agriculture, and large-scale migration to cities.[32] However, there can also be a reverse displacement, where large numbers of workers migrate to work on large-scale plantations, as in the case of oil palm cultivation in Indonesia and Malaysia.[33] Vulnerable social groups, including indigenous people, are most at risk of displacement, which also gives this phenomenon a socio-cultural context. Indigenous peoples of South America, Africa and Asia are suffering due to deforestation and unsustainable land conversion. In India, Indonesia and the Philippines, indigenous peoples have been tricked into selling their lands and those who defend them are being increasingly threatened and criminalised.

Table 1.3 Land grabbing extent and area examples

Macro region	*Number of deals*	*Number of ha*	*Countries of the microregion, where land grabbing most often occurs*	*Examples of the key investing countries (No. of deals[28]/ha)*	*Comments*
Africa	566	12 379 209	Liberia. Ethiopia	Liberia: Italy 2/310 932; USA2/280 300; Malaysia 4/259 60 Ethiopia: Saudi Arabia 13/319 903 India 18/176 303.34 UK 3/131 128	In Africa 90% of deals concerns crops and 10% livestock. Ethiopia experiencing land grabbing process has an investment: Mozambique 1 deal for 2 000 ha
Asia	529	9 286 108	Indonesia	Malaysia 82/1 410 328.1 Singapore 46/ 1 005 642.29 Hong Kong 13/845 577	In Asia 94% of deals concern crops and 2% livestock. The remaining 4% are for non-renewable resources. Indonesia experiencing land grabbing has its investments in Vietnam: 6 deals covering 319 300 ha and in Liberia 1 deal 220 000 ha
Oceania	32	3 424 263	Papua New Guinea	United States of America 3 deals 2 043 097 ha Malaysia 21 deals 818 555 ha China. Hong Kong Special Administrative Region 3 deals 494 010 ha	In Oceania 76% deals concern crops and 24% livestock
Eastern Europe	276	3 489 100	Ukraine	Cyprus 76 deals 1 595 767.62 ha Luxembourg 55 deals 743 076 ha United States of America 53 deals 639 504 ha	In Eastern Europe 87% of the deals concern crops. 13% livestock.

Source: Own elaboration based on landmatrix.org (accessed: 11/01/2024).

In Africa, over 50% of the population is employed in agriculture. Land grabbing is therefore a problem for their livelihoods, but displacement is not just an effect of foreign investment, but, to a distinctive extent, is also due to land deals made by African chiefs with foreign actors and the agricultural projects of governments in African countries. Most of those incidents take place on customary land, belonging to ordinary African people, whose land rights are neglected. Finally, to provide an example from South America, Brazil, during the period of Bolsonaro's presidency, faced administrative decisions regarding the deforestation of the Amazon forest in Brazil, the aim of which was to develop agriculture and infrastructure, which have in fact resulted in ecocide through large-scale environmental degradation accompanied by historical genocide and the ongoing dispossession of indigenous peoples.

Another threat associated with an improperly implemented bioeconomy is similar to the threats associated with the linear economic model and concerns the unfair distribution of the benefits of the bioeconomy – 'bioinequalities' – which can be seen as a result of the neoliberal approach to capital present in recent decades. This is not only a question of the inequalities resulting from the above-mentioned deprivation of property rights or land grabbing. This problem also translates to the international level, where the lack of change in values and approach to the economic paradigm threatens to perpetuate the division along the Brandt line, where the rich North develops technologies and innovations, while the poor South provides resources, in this case, bioresources.

The circular (bio)economy as a path to sustainability will not change the social and ecological reality unless the values of the Doughnut Economy model become its overarching principle. The economic effects of merely changing the raw material for production while continuing to do 'business as usual' will contribute neither to better meeting the needs of the poorer parts of the world, nor to the elimination of environmental externalities of production.

The shift from quantitative growth towards qualitative development is essential for future generations. This means that the global economic system needs a fundamental process of transformation towards a knowledge-based bioeconomy to overcome the current dependence on fossil-based production. To achieve this, it is also necessary to launch processes of the generation and diffusion of knowledge and values within the quadruple helix of administration, business, scientific and research institutions and civil society.

1.5 Socio-economic perspective of the bioeconomy in Europe

To assess the state of the bioeconomy and its potential impact on the socio-economic situation, it is necessary to refer to its metrics. Due to its roots in biological processes and ecosystems, describing the level of development of the bioeconomy is a difficult task. The bioeconomy monitoring system in the EU is based on data collected in 5 key areas and several subcategories of variables (Figure 1.6).

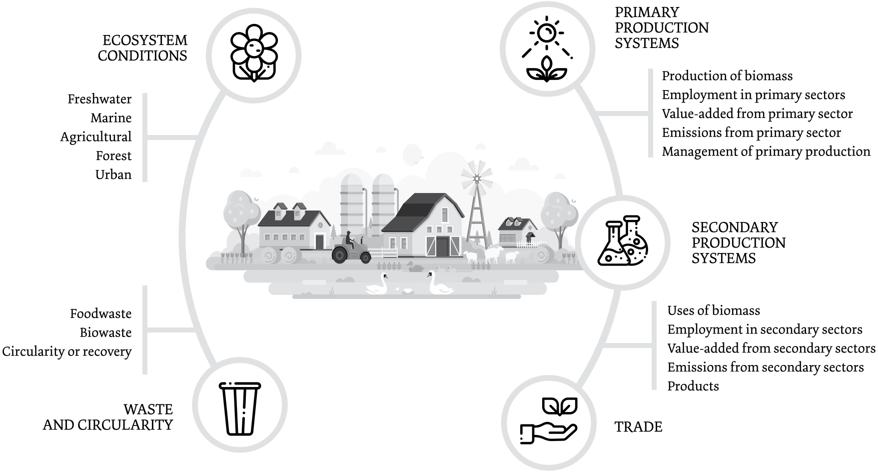


Figure 1.6 The bioeconomy monitoring system.

Source: Adapted from: Knowledge Centre for Bioeconomy: https://knowledge4policy.ec.europa.eu/bioeconomy/monitoring_en.

To understand the direction of development of the bioeconomy in EU, 11 detailed indicators corresponding to the monitoring areas planned by the EC were selected.[34] Additionally, the analysis included the presence of a bioeconomy strategy (at the national level) and the eco-innovation index and government support for agricultural research and development (by sector) in EUR per capita. The data, depending on the phenomenon, present the situation for the years 2019–2022.

These variables (for the period 2018–2021), after standardisation, were used to build a Czekanowski matrix. This method creates a matrix of distance measures, where individual numerical values are replaced with appropriately selected graphic symbols. This allows connections between the objects in the analysed set and its division into groups – if any – to be revealed.[35] Use of Czekanowski's method revealed the existence of several groups in the model of bioeconomy development in European countries (Figure 1.7).

The larger the dot, the stronger the similarities between countries. There was therefore a high level of diversification in the potential and shape of the bioeconomy in the period analysed. There is a strong group of member states that joined after 2004, although this group also includes Greece and Portugal. Germany, France, Italy and Austria form a strong cluster, while the Benelux countries, Romania together with Bulgaria and Sweden together with Finland, each constitute clusters which seem to be on an individual path. The division of Europe in terms of the shape of the bioeconomy seems to run along conventional lines – Western and Northern Europe vs. Central and Southern Europe. These similarities may be temporary. However, the observed clusters may provide information about potential diversification in the functions of the

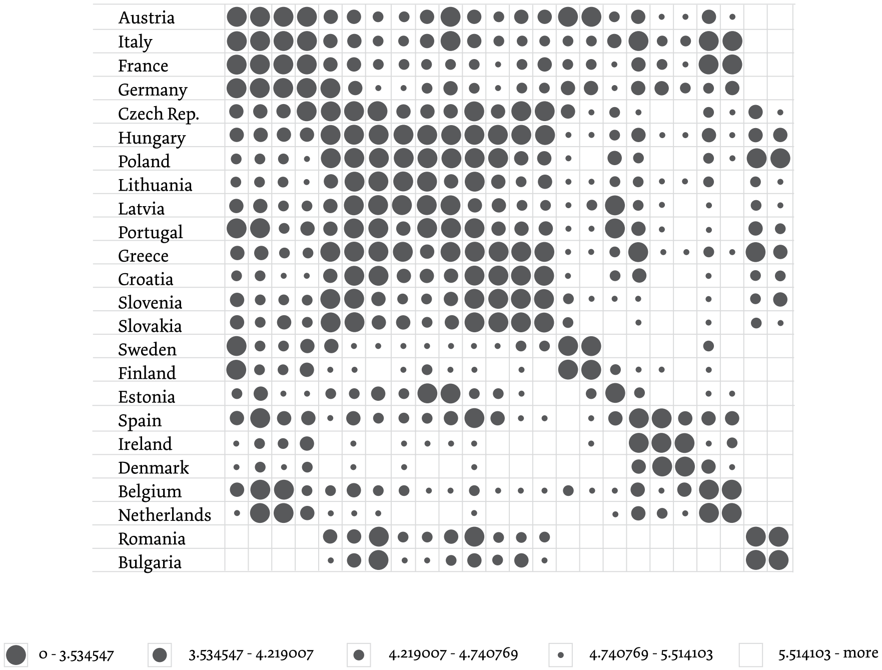


Figure 1.7 Czekanowski's Matrix (2018/2021): Clusters of similarities in the area of the bioeconomy.

Source: Own elaboration, MaCzek 3.0.

bioeconomy in Europe, such as, for example, between the bioeconomy of Finland and Sweden, which is strongly based on knowledge and forest resources, compared to the bioeconomy in Romania and Bulgaria; based on traditional agriculture. Due to such differences, socio-economic development will thus be shaped differently in both pairs of countries too. To better understand the differences in the potential and progress of the bioeconomy, let us now take a closer look at the selected indicators.

Figure 1.8 shows the percentage of the population employed in various sectors of the bioeconomy, compared to the percentage of the population employed specifically in agriculture.

The bioeconomy leads to the creation of numerous jobs in the future, especially in regions closely linked to agricultural production and fisheries. This is done by increasing the share of raw material producers in regional bioeconomies. According to industry estimates, up to 1.5 million new jobs may be created in the industry focused on the development of biotechnology by the end of this decade.[36] In EU member states, the annual turnover in the bioeconomy is worth approximately EUR 2.3 trillion and employs approximately 18 million people.[37]

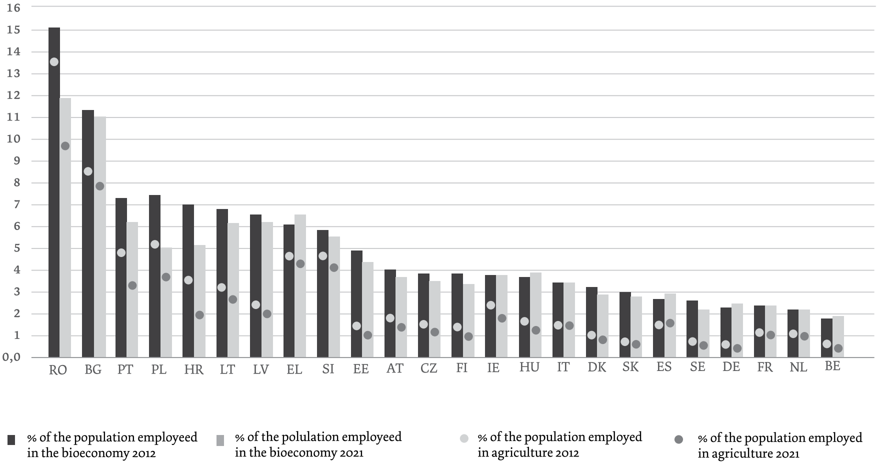


Figure 1.8 Population employed in the bioeconomy vs population employed in the agricultural sector.

Source: Own elaboration, based on data collected by: https://knowledge4policy.ec.europa.eu/visualisation/eu-bioeconomy-monitoring-system-dashboards_en.

Employment in agriculture is largely responsible for employment in the bioeconomy sector (Figure 1.9). As can be seen from Figure 1.8, in the period from 2012 to 2021, non-agricultural sectors of the bioeconomy are starting to play an increasingly important role. Growth in total employment in the bioeconomy, with a simultaneous decline in employment in agriculture, was visible in Greece, Ireland, Hungary, Germany, France, the Netherlands and Belgium.

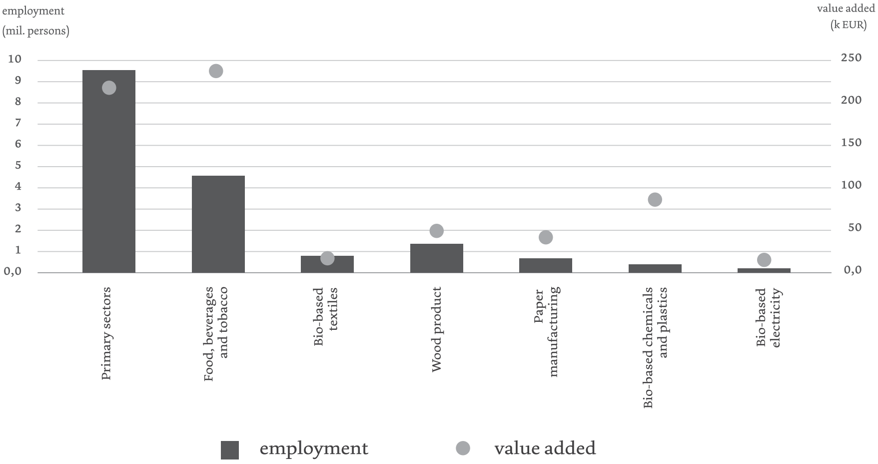


Figure 1.9 Employment in sectors of the bioeconomy, 2020 (% of employed).

Source: Own elaboration, based on data: Jobs and Wealth in the European Union Bioeconomy https://datam.jrc.ec.europa.eu/datam/mashup/BIOECONOMICS/.

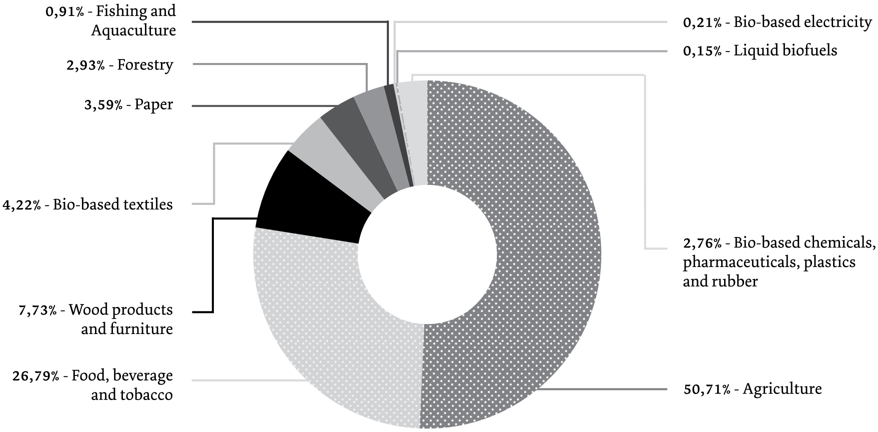


Figure 1.10 Employment and value added by sectors of the bioeconomy in 2020 (EU-27).

Source: own elaboration, based on data: Lasarte-López, J., M'barek, R., Ronzon, T. and Tamosiunas, S. (2023). EU Bioeconomy Monitoring System indicators update, EUR 31531 EN, Publications Office of the European Union, Luxembourg.

In the EU, over the period from 2008 to 2020, a decline in employment was observed in the still dominant, traditional sectors of agriculture, biobased textiles, wood industry, fishing and aquaculture. At the same time, the number of employees in these areas of bio-based electricity, liquid biofuels, bio-based chemicals and materials increased to the greatest extent and there were the most innovations implemented in economic life. This is, of course, interdependent with the level of growth in the added value (see Figure 1.10) of individual sectors of the bioeconomy.

The advantage of strengthening the potential of bioeconomy sectors is its buffer role in times of economic crises, regardless of their differences in origin. These observations are confirmed by the economic situation resulting from the economic crisis of 2008 or the economic consequences of the COVID-19 pandemic. Bioeconomy sectors tend to increase rates of unemployment less than other sectors of the economy in EU countries. Therefore, the apparent low labour productivity in the bioeconomy of eastern and southern member states may reveal a high capacity for growth in employment, strengthening the resilience of the sector.[38] A significant share of agricultural workers involved in production in the bioeconomy suggests that the transformation of regions closely linked to agricultural production can bring gains in efficiency thanks to the development of the bioeconomy, and in particular of biomass-based energy production.

The bioeconomy sectors with the highest labour productivity are bioelectricity production followed by the manufacturing of bio-based chemicals, pharmaceuticals, plastics and rubber. The lowest labour productivity is in agriculture and bio-based textiles. Therefore, focussing on biomass production in the agriculture, textiles, forestry, fisheries, and aquaculture sectors, like for example in Southern and Central Europe, results in lower-than-average labour productivity levels in almost all sectors of the bioeconomy. Higher labour productivity in the bioeconomy is characteristic of the group of countries of Northern and Western Europe that have diversified their own bioeconomy towards the production of bioelectricity, biochemicals, bioproducts, pharmaceuticals or plastics of biological origin. Consolidating this model may pose a threat to the levelling out of socio-economic differences between groups of countries in the EU, along already existing lines.

The area of the non-service-related bioeconomy is represented by the four economies of Belgium, Denmark, Finland and Ireland. As Ronzon et al.[39] note, in terms of labour productivity, these economies are already highly productive and have experienced gains in productivity over the last few years. This success can be attributed mostly to the strategic policies of these countries in the area of Green Deal policy. The bioeconomy sectors of Western European countries (Austria, France, Germany, Italy and Spain) are, however, also productive, but with lower rates of growth in productivity and weaker structural changes. Most of them have national or regional bioeconomy strategies. The remaining EU member states, including all those in Central Europe, except for Latvia, show levels of labour productivity below the European average. Therefore, it is difficult to talk about the transfer towards a circular bioeconomy being made in EU countries for now.

The pursuit of strategies related to the development of the bioeconomy at the regional level has its economic justification. In the knowledge-based regional bioeconomy, both investment and growth are key to jobs, income growth and regional competitiveness. The development of the bioeconomy has a significant impact on increasing the region's ability to attract investment and raising the standard of living of its inhabitants.

In conclusion, the assimilation of circular economy principles, with a specific emphasis on the bioeconomy, exerts a profound influence on economic development through the optimisation of resource efficiency, the realisation of cost savings, the stimulation of innovation, the facilitation of job creation, the improvement of workforce skills and the enhancement of environmental resilience. The results of this explorative scientific study underscore the imperative for policymakers, businesses, and stakeholders to ardently embrace and implement circular economy practices, particularly within the bioeconomic context, as a strategic pathway towards achieving sustainable and resilient economic development at both a national and a regional level.

1.6 Financing sustainable development and the bioeconomy

A sustainable future requires proper support from the financial sector. This sector has a large impact on shaping reality, because it is there that decisions about financing development are made. The financial sector in the conventional sense is focused on generating and maximising profit and does not take the multidimensional aspects of sustainable development into account. Faced with the challenges of today, it is not sufficient to allocate expenditure of financial resources simply based on the criterion of economic efficiency when making decisions about the financing of a project. Calculating financial needs in the context of achieving 2030 Sustainable Development Goals (SDGs) does not always take the role of policy and the institutional environment into account. Weak institutions, poorly functioning governments and corruption make it difficult to achieve these goals.[40] It is beyond dispute that sustainable development is of strategic importance for the long-term competitiveness of a safe, climate-resilient and resource-efficient circular economy that makes economic growth independent of the use of fossil resources. However, financial support is necessary to achieve Sustainable Development Goals and to finance the transformation of the economy towards a sustainable, circular economy and the bioeconomy.

United Nations estimates assume that achieving the 2030 SDGs will require investments of US$5 to 7 trillion (trillion) per year between 2015 and 2030.[41] According to OECD estimates, before the COVID-19 pandemic, developing countries were $2.5 trillion short of annual funding for the SDGs, and the impact of COVID-19 could increase the sustainability financing gap in developing countries by 70%, or $1.7 trillion. In the 2021 Financing for Sustainable Development Report, the UN warned that COVID-19 could mean a lost decade for sustainable development. In 2022, the risk materialised. The full-scale war in Ukraine and the resulting increase in food and energy prices have exacerbated challenges for many countries and hampered progress towards achieving the Sustainable Development Goals. Despite some positive signals coming from the economy, the future remains uncertain, especially for the poorest countries struggling with growing debt. Banking also experienced slumps in the United States and Switzerland. All these events caused the financial gap and the difference in development perspectives to become even wider. To prevent this crisis from deepening, additional mechanisms should be developed to finance sustainable development, and it is therefore necessary to seek new sources of financing the development and adaptation of financial systems. Sustainable finance and sustainable financing are the response to this demand.

The term *sustainable finance* is most often understood as a concept which attempts to reconcile the concept of sustainable development and finance from the perspective of neoclassical economics. However, s*ustainable financing* is a term referring to the consideration of social and environmental factors in the process of making decisions regarding the allocation of capital. This is possible as a result of the inclusion of three perspectives in decision-making and risk management processes, i.e. the environmental perspective (Environmental), the social perspective (Social) and economic governance (Governance). Sustainable finance and financing takes into account the need to counteract the negative impact of market participants' activities on the natural environment, such as soil, water and air pollution, and social inequalities.

A unified classification system for sustainable activities has been created. In the European Union, the EU Taxonomy is the foundation for the operation of financial institutions, i.e. redirecting capital flows towards more sustainable activities. Work on the development of the EU Taxonomy is carried out via he Sustainable Finance Platform. The general assumptions regarding the EU Taxonomy are included in Regulation 2020/852[42] of the European Parliament and of the Council. Clear criteria for identifying sustainable investments are intended to facilitate investment in such a way that, in accordance with the provisions of the European Green Deal, climate neutrality is achieved in Europe by 2050.[43]

Criteria for qualifying an activity as sustainable

1 Significant contribution to at least one of six environmental goals

- Protection and restoration of biodiversity and ecosystems
- Mitigating climate change
- Adaptation to climate change
- Pollution prevention and control
- Protection of marine resources and their sustainable use
- Shift to a circular economy

2 Technical screening criteria (TSC)
3 No harm to environmental objectives (do no significant harm (DNSH)). For each action, the TSC provide thresholds to determine the absence of significant harm.
4 Guarantees of respect for human rights and labour standards.

Source: EU Taxonomy

The classification is aimed at members of the European Union, financial market participants offering financial products, and entities subject to non-financial reporting obligations. Entrepreneurs wishing to obtain funds from European funds for sustainable activities should also employ this classification system. The classification system is intended to be a list of types of environmentally sustainable economic activities containing detailed qualification criteria, thresholds and indicators implemented by EC-delegated acts.

Ongoing work on the EU Taxonomy has identified eligibility criteria for activities that aim to mitigate climate change and help adapt to climate change as part of meeting environmental objectives (Table 1.4).

The EU Taxonomy introduces two additional classification categories to enable activities to be recognised as sustainable that would not otherwise be considered sustainable but still contribute to promoting sustainable development. These are *enabling activities* and *transitional activities*. Enabling activities help contribute to the objectives of the EU Taxonomy. However, they must not lead to the undermining of long-term environmental objectives and must

Table 1.4 Eligibility criteria for activities contributing to climate change mitigation and adaptation

Industry	*Operations*
Power engineering	Energy production from various forms of renewable sources, cogeneration, transmission, distribution and storage of energy;
Forestry	Afforestation, forest restoration, forest management, forest protection;
Agriculture	Cultivation of perennial and non-perennial plants, animal production;
Industry	Production of low-emission technologies, cement, iron, steel, aluminium, hydrogen, basic organic and inorganic chemicals, fertilisers, nitrogen compounds and plastics;
Transportation	Rail freight and passenger transport, public transport, infrastructure for low-emission transport, inland waterway transport for freight and passengers;
Information and communication technologies	Data processing, data-driven greenhouse gas emission reduction solutions;
Real estate and construction	Building renovations, new construction facilities;
Sewage and waste management, water supply	Sewage treatment, sewage sludge fermentation, waste collection, transport and segregation, biowaste fermentation and composting, waste recovery and recycling, capture and use of gases from landfills, and CO_2 capture and transport; water collection, treatment and supply;
Professional, scientific and technical activities	Design and technical advice on adaptation to climate change;
Financial and insurance activities	Insurance, except life insurance.

Source: Own elaboration.

have an impact on the environment throughout the life cycle of the activity. In turn, transitional activities are intended to stop global warming in accordance with the provisions of the Paris Agreement. Transitional activities must not have low-emission alternatives that are economically or technologically feasible, must meet strict emission standards and must not block or hinder the implementation of low-emission alternatives.[44]

Reporting non-financial data is becoming a key element in investment decisions. Asset managers, investors and lenders expect additional information from companies related to environmental, social and governance (ESG) data. The ESG reporting framework is created by international standards and regulatory requirements, such as the Taxonomy Regulation (in the EU) and, at a global level, the recommendations of the Task Force on Climate-related Financial Disclosures (TCFD), as well as the Sustainable Finance Disclosures Regulation (SFDR) and the Non-Financial Reporting (NFR) Directive.

Disclosure requirements include the environmental and social impact of a company's activities, as well as the business and financial risks a company faces in its sustainability activities. ESG risks may negatively impact assets, financial situation and profitability or reputation.

Bioeconomy entities will also be obliged to prepare ESG reports. Bioeconomy, as an economic method that aims to find solutions to the environmental crisis without slowing down the economy, focuses in particular on ecosystem products and services. The bioeconomy was equipped with institutions such as an information system, a platform for collecting knowledge, and was introduced into development strategies such as "Europe 2020 – a strategy for smart, sustainable and inclusive growth" or "Horizon 2020 – a programme for financing scientific research and innovation in Europe". The development of the bioeconomy means the need to strengthen economic ties with science, business, and the social environment. This creates the opportunity to reach for various sources of financing the bioeconomy. Apart from the obvious sources that are specific to running a business, such as private investments, bank loans and credits, including those from the European Investment Bank, which is becoming a bank financing activities for climate and environmental sustainability,[45] the involvement of entities from various sectors of the economy gives the opportunity not only to apply for EU funds, but also to look for opportunities to finance investments in the bioeconomy from other, less conventional sources, such as crowdfunding or impact investing.

According to the provisions of the Bioeconomy Strategy, agricultural systems account for almost 75% of employment in the bioeconomy. However, farmers and individual farms do not have the technical and financial resources to work on increasingly efficient implementation of the assumptions of the bioeconomy. It is conventional sources of financing, and EU programmes in particular, especially the Horizon Europe programme (2021–2027) financed by the European Commission under Cluster 6, that will support the development of the bioeconomy. Apart from Horizon, financing can be found in other programmes, such as LIFE, which co-finances projects in the field of climate and environmental protection. The new regulation defining the rules of the programme for 2021–2027 allocates funds to support the circular economy.[46]

Of course, by definition, bioeconomy entities should be interested in sustainable investments and sustainable investment financing. Financing the bioeconomy and circular bioeconomy, as well as other elements which play an important role in the climate transformation, is not only supported by public or bank funds. Building a framework for sustainable finance also includes activating and using private funds to finance sustainable investments. They are raised particularly in the growing sustainable bond market. Currently, sustainable bond issuance standards are being developed and updated by the International Capital Market Association (ICMA), which has published the Green Bond Principles (GBPs), Sustainability Bond Guidelines (SBGs), Social Bond Principles (SBPs) and Sustainability-Linked Bond Principles (SLBPs). The Climate Bonds Initiative (CBI) is an organisation that has developed an alternative bond standard and certification scheme (Table 1.5).[47]

Table 1.5 Types of sustainable bonds

Type	*Description*
Green Bond	Partial or total financing or refinancing of new and/or existing green projects
Social Bond	Financing projects involving investments with clear social values
Sustainability Bond	Financing projects combining ecological and pro-social projects
Sustainability-Linked Bond	The bond issuer indicates sustainability performance targets (SPTs) and key performance indicators (KEIs). If they are not achieved, the bond interest rate increases (step-up clause)

Source: own elaboration.

According to the World Bank, by September 2023, the total amount of green, social, sustainable and sustainability-linked bonds issued reached US$4.7 trillion, of which green bonds account for 63% and emerging market issues 16% of the total amount.

It is therefore clear that there is a gradual change in the functioning of financial markets, which are intended to facilitate the climate transformation by influencing the economy, including the development of a circular bioeconomy. Any company that wants to stay on the market will have to demonstrate that it operates in a way that takes ESG factors into account. Otherwise, it will lose investor interest and the chance to obtain financing and develop.

Notes

1 Aristotle, Politics, transl. B. Jowett, Batoche Books, Kitchener, 1999, p. 17.

2 Own elaboration: Madison Project, Working Paper WP-15, https://www.rug.nl/ggdc/historicaldevelopment/maddison/publications/wp15.pdf. Carbon Brief, 2021 and Met Office: Atmospheric CO2 now hitting 50% higher than pre-industrial levels, https://www.carbonbrief.org/met-office-atmospheric-co2-now-hitting-50-higher-than-pre-industrial-levels/ and WWF, 2022, Living Planet Index, https://livingplanet.panda.org/en-US/.

3 Richardson K., et al., 2023. Earth beyond six of nine planetary boundaries. *Science Advances*, 9, eadh2458. https://doi.org/10.1126/sciadv.adh2458.

4 Ricardo, D., *On the Principles of Political Economy and Taxation*, Batoche Books, Kitchener, 2001 (1817), 41.

5 Gomes da Silva, F. J., Gouveia, R. M., 2019. Global Population Growth and Industrial Impact on the Environment. Cleaner Production, 33–75. https://doi.org/10.1007/978-3-030-23165.

6 Smith, K. *The Malthusian Controversy*, Routledge, New York, 2013 (1951).

7 The law of diminishing returns in agriculture was at the heart of Ricardian economics and was the main premise of Malthus's population theory. According to this law, by increasing the inputs of one factor by further units and keeping the inputs of other factors unchanged, a point is reached from which further increases in the amount of this factor result in a decrease in the marginal increases in total production.

8 Foster, J. B., 1999. Marx's theory of metabolic rift: Classical foundations for environmental sociology. *American Journal of Sociology*, 105(2), 366–405. https://doi.org/10.1086/210315.

9 Górka, K., Poskrobko, B., Radecki, W. Ochrona środowiska (Protection of the Environment). PWE, Warsaw 2001.

10 Żylicz, T., 2009. Twierdzenie Coase'a (Coese's theorem). *Aura*, nr 7.

11 Fiedor, B. (ed.), 2002. *Podstawy ekonomii środowiska i zasobów naturalnych (Fundamentals of Environmental and Natural Resource Economics)*, C. H. Beck, Warsaw.

12 Pater, B. 2020. *Funkcjonowanie i finansowanie parków narodowych w Polsce (Functioning and Financing of National Parks in Poland)*. Difin, Warsaw.

13 Brundtland, G. H., 1987. Our Common Future: Report of the World Commission on Environment and Development. Geneva, UN Document A/42/427.

14 Treaty on European Union and Treaty on the Functioning of the European Union (consolidated version), OJ EU Laws, C 202, Volume 59, 7 June 2016.

15 Georgescu-Roegen, N., 1977. Inequality, limits and growth from a bioeconomic viewpoint. Review of Social Economy, 35 (3), 361–375.

16 Lasarte-López, J., Piotrowski, S., M'barek, R., Carus, M., Tamošiūnas, S., 2022. Jobs and wealth in the EU bioeconomy / JRC – Bioeconomics. European Commission, Joint Research Centre (JRC) [Dataset] PID: http://data.europa.eu/89h/7d7d5481-2d02-4b36-8e79-697b04fa4278.

17 McCormick, K., 2010. The Knowledge-Based Bio-Economy in Europe. Contribution to conference: Knowledge Cities World Summit (16–19. 11. 2010).

18 Martinez, J., 1998. Genomics and the World's Economy. Science Magazine, 281: 5379, 925–926.

19 Adamowicz, M., 2017. Biogospodarka – koncepcja, zastosowanie i perspektywy (Bioeconomy – Concept, Application and Prospects). Zagadnienia Ekonomiki Rolnej (Agrieconomics Issues). Warsaw, 1(350), 29–49.

20 OECD, 2009. *The Bioeconomy to 2030: Designing a Policy Agenda*, OECD Publishing, Paris, https://doi.org/10.1787/9789264056886-en.

21 Hall, R. et al., 2012. Bio-economy versus Biodiversity. Global Forest Coalition, 18.

22 European Commission (EC), 2012. Innovating for Sustainable Growth: A Bioeconomy for Europe; COM (2012) final; European Commission: Brussels, Belgium.

23 European Bioeconomy Stakeholders. Manifesto. 2017. https://knowledge4policy.ec.europa.eu/publication/european-bioeconomy-stakeholders-manifesto_en.

24 EC, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A sustainable Bioeconomy for Europe: Strengthening the connection between economy, society and the environment. COM/2018/673 final.

25 EC, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A new Circular Economy Action Plan For a cleaner and more competitive Europe. COM/2020/98 final.

26 European Commission, 2022. Directorate-General for Research and Innovation. Adoption of the bioeconomy strategy progress report. Publications Office of the European Union, Luxembourg.

27 In this book, the term circular (bio)economy is used to emphasise the element of biological (renewable) resources in the more general concept of the circular economy.

28 The Land Matrix defines a land deal as any intended, concluded, or failed attempt to acquire land through purchase, lease, or concession for agricultural production, timber extraction, carbon trading, renewable energy production, industry, mining, oil and gas extraction, conservation, tourism and land speculation in low- and middle-income countries.

29 Borras, S. M., Franco, J. C. 2013. Global Land Grabbing and Political Reactions "From Below." Third World Quarterly, 34(9), 1723–1747. https://doi.org/10.1080/01436597.2013.843845.

30 Baker-Smith, K. Szocs Boruss, M. A. What is land grabbing – a critical review of existing definitions (report). Eco Ruralis, 2016.

31 Liao, C., Jung, S., Brown, D.G., Agrawal, A. 2020. Spatial patterns of large-scale land transactions and their potential socio-environmental outcomes in Cambodia, Ethiopia, Liberia, and Peru. Land Degradation & Development, 31, 1241–1251. https://doi.org/10.1002/ldr.3544.

32 Backhouse M, Lühmann M, Tittor A. 2022. Global inequalities in the bioeconomy: Thinking continuity and change in view of the global soy complex. *Sustainability*, 14(9), 5481. https://doi.org/10.3390/su14095481.

33 Backhouse, M., Lehmann, R., Lorenzen, K., Puder, J., Rodríguez, F., Tittor, A. 2021. Contextualizing the bioeconomy in an unequal world: Biomass sourcing and global socio-ecological inequalities. In: Backhouse, M., et al. *Bioeconomy and Global Inequalities*, Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-030-68944-5_1.

34 The following were selected as indicators presenting ecosystem conditions:

- Utilised Agricultural Area (UAA) as a % of the country's area.
- Nature 2000.

The following indicators were selected in the area of waste and circularity:

- Circular material rate.
- Food waste, in tonnes per capita.

The following variables were selected in the area of primary and secondary production:

- Domestic Material Consumption (Biomass) %.
- Gross value added per person employed in the bioeconomy (total of 1 000 EUR/employee).
- Share of employees in various sectors of the bioeconomy.
- Bioeconomy sector turnover as a % of GDP (constant, 2015).

35 Jaskulski, P., Sołtysiak, A. 2004. Diagram Czekanowskiego: pomysł, historia, zastosowania (Czekanowski diagram: idea, history, applications). Prace Naukowe AE we Wrocławiu. Taksonomia, t. 11, nr. 1022. Klasyfikacja i analiza danych – teoria i zastosowania, 374–383.

36 Debergh, P., Bilsen, V., Van de Velde. 2016 EuropaBio. Report. Jobs and growth generated by industrial biotechnology in Europe, Brussels, Belgium.

37 Ronzon, T., M'Barek, 2018. European Commission's Knowledge Centre for Bioeconomy, https://doi.org/10.3390/su10061745.

38 Ronzon, T., Piotrowski, S., Tamosiunas, S., Dammer, L., Carus, M., M'barek, R. 2020. Developments of economic growth and employment in bioeconomy sectors across the EU. *Sustainability*, 12, 4507.

39 Ronzon, T., Iost, S., Philippidis, G. 2022. Has the European Union entered a bioeconomy transition? Combining an output-based approach with a shift-share analysis. *Environment, Development and Sustainability*, 24, 8195–8217.

40 Vorisek, D., Yu, S., 2020. Understanding the Cost of Achieving the Sustainable Development Goals. Policy Research Working Paper No. 9146, World Bank Group, 3.

41 Vorisek, D., Yu, S., 2020. Understanding the Cost of Achieving the Sustainable Development Goals. Policy Research Working Paper No. 9146, World Bank Group, 3.

42 Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088.

43 Delivering the European Green Deal: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en.

44 Lewiatan Confederation, 2021. *Zrównoważone finanse – Krótki przewodnik dla firm (Sustainable finance – A short guide for companies)*, Lewiatan, Warsaw, 29.

45 EIB Group Climate Bank Roadmap 2021-2025, November 2020.

46 Regulation (EU) 2021/783 of the European Parliament and of the Council of 29 April 2021 establishing a Programme for the Environment and Climate Action (LIFE), and repealing Regulation (EU) No 1293/2013.

47 Lewiatan Confederation, 2021. *Zrównoważone finanse – Krótki przewodnik dla firm (Sustainable finance – A short guide for companies)*, Lewiatan, Warsaw, 29.

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2 Institutional environment of the bioeconomy from a theoretical perspective

Renata Śliwa and Małgorzata Pink

2.1 Introduction

The special feature of the circular bioeconomy lies in the complexity of the value chain, or, more precisely, in the relationships/transactions between the entities in the chain. In contrast to the relatively simple value chain of products from non-renewable raw materials, where we are dealing with a linear process, in a circular bioeconomy, there are additional links and interdependencies resulting from the use of by-products, by-streams and – to avoid the term 'waste' – recovered materials. The complexity of the relationships between economic entities in the value chain (Figure 2.1[1]) leads to greater complexity of the institutional environment.

The flows of renewable resources from producers take place not only towards the markets of final goods, but also between the sectors of industrial goods, food and feed, fuel, energy and fertiliser producers. The circular bioeconomy model enables the value of biomass to be fully used (see the bioeconomy value pyramid – Figure 6.1) assuming the willingness to cooperate between stakeholders and potential partners and their awareness of applications and properties of biomass. These transactional relations are embedded in a new legal and organisational frameworks (see Chapter 3) and engage with the part of public opinion and civil society, for which the evolution of the economic system towards a form which allows negative impact on the environment to be reduced is a key issue. They require an innovative approach and rapid technological progress, as well as sources of financing, the purpose of which capital is not only to multiply capital, but also to use it to solve problems (see subchapter 1.6 Financing sustainable development and the bioeconomy) – and the generation of added value not only in economic, but also in social and ecological categories.

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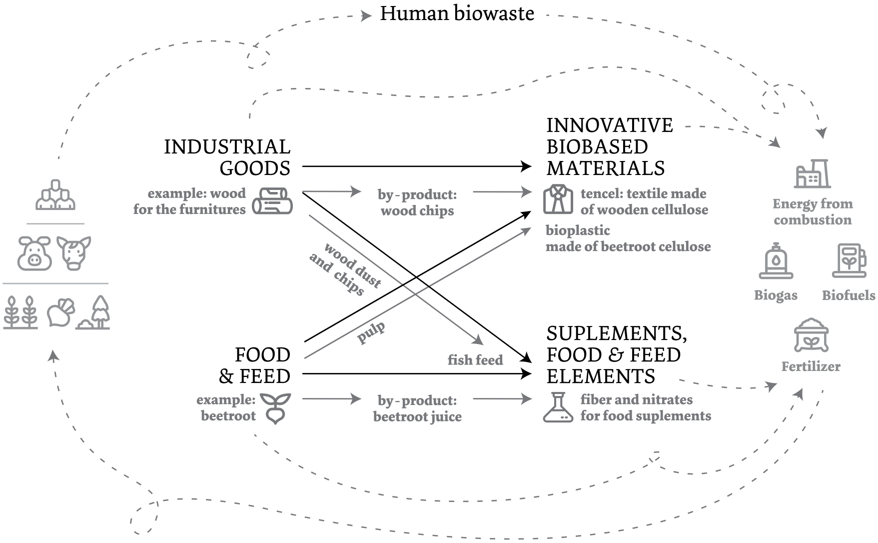

Figure 2.1 Dependencies in the value chain in the circular bioeconomy.

Source: own elaboration.

The interdependencies of the functioning of the bioeconomy outlined in this way provide fertile ground for analyses of institutional economics. This research perspective emphasises the concept of institution which, according to Douglas North, a key representative of New Institutional Economics, can be defined as

> *…the humanly devised constraints that structure political, economic and social interaction. They consist of both informal constraints (sanctions, taboos, customs, traditions, and codes of conduct), and formal rules (constitutions, laws, property rights) (…) Institutions provide the incentive structure of an economy; as that structure evolves, it shapes the direction of economic change towards growth, stagnation, or decline.*[2]

This is how we will understand the institutions here, taking their evolutionary aspect into account. The bioeconomy, the circular economy and the social economy are expressions of the evolution of the approach to production and consumption. An evolution forced, among other things, by negative changes in planetary boundaries, including the impact of greenhouse gas emissions.

The achievement of the status of a widespread economic model by the circular economy, including the bioeconomy, is related to an understanding of the interrelationships with its institutional environment and the changes required thereto The multi-layered nature of the circular bioeconomy makes conducting an analysis of the institutional environment a difficult task.

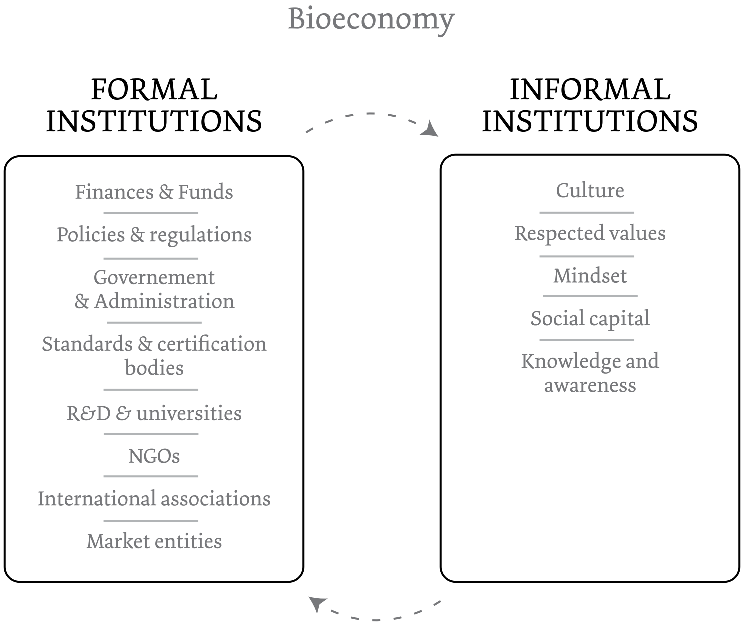

Figure 2.2 Examples of institutions creating the environment of the bioeconomy.

Source: Own elaboration.

Examples of formal and informal institutions that influence the evolution towards a circular bioeconomy are listed in Figure 2.2.

The complexity of the network of connections of bioeconomy stakeholders is additionally strengthened by the relationship of the bioeconomy to Nature, which is a reservoir of, among other things, common pool resources. Under the conditions of the bioeconomy, the role not only of cooperation, but also of competition between various administrative units (state, local government – both in the territorial and professional spheres, and local/civic and educational authorities, etc.), which give these areas of economic governance their polycentric features, is particularly important. However, polycentricity as a system for decision-making between formally independent centres of power may also take the form of an interdependent system of relationships.

2.1.1 *Conceptual outline of the issues of formal institutions in the bioeconomy – institutional environment, governance structures, co-creation of rules of conduct, interdependent systems of relationships*

Institutions as established principles and standards provide the foundation for understanding the organisation and functioning of economies. Their role as *the rules of the game in society* arises not only from them creating *frameworks* for *human interactions*,[3] but also, where formal and informal institutions are concerned, equips social and economic entities with incentive structures determining processes of socio-economic activity and determines their consequences.

The institutional view of economic activities makes a distinction between the institutional environment and organisations to show the different institutional layers which may be encountered when identifying the course of processes and the formation of structures in the economy. The institutional environment establishes the basis for production, exchange and distribution It is the set of fundamental political, social and legal rules on which the economic environment is built through determining the rules governing elections, the granting of property rights and the right of contract.[4] Organisations are understood as specific groups of individuals pursuing a mix of common and individual goals,[5] with their own internal institutional structures that influence the way both members of those organisations and people from outside of those organisations behave. The institutional environment is perceived as a set of rules and norms which create a framework for determining the security of property rights and the enforcement of contracts, while ensuring the efficiency and impartiality of the judicial system, and providing incentives and improving the capacity of state actors to protect order and provide broad-based public goods, control violence, curb the abuse of power, and so on.[6] This specific macro layer of institutions is combined together with micro and meso layers (Figure 2.3). The micro layer refers to the rules and norms found in organisations as institutional structures (determining how transactions are organised, the division of labour, the incentives to produce and invest, and so on). The meso layer consists of institutions which address specific domains of economic and social life – institutions that operate based on regulations and norms between the governmental and societal rules of the macro layer and the rules governing the activity of organisations and the functioning of markets in the micro layer. From the point of view of institutional analyses conducted in the area of the bioeconomy, it is important to emphasise the key role of the layer

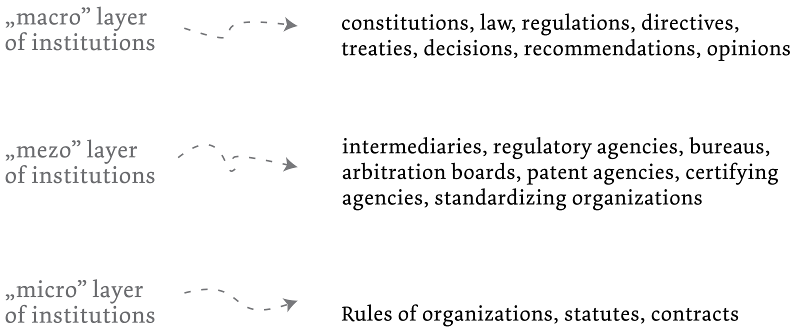

Figure 2.3 Layers of the institutions.

Source: Own elaboration based on North D. C., *Institutions, Institutional Change and Economic Performance*, Cambridge University Press 1990; Claude Ménard, Meso-institutions: The variety of regulatory arrangements in the water sector, *Utilities Policy*, Volume 49, 2017, pp. 6–19.

of meso institutions, alongside the layer of macro institutions and the layer of micro institutions, by providing examples of institutional domains, such as regulatory agencies, patent agencies, and certifying and standardising organisations. These structures in the meso layer act as intermediaries, implementing macro rules in specific domains, enforcing applicable rules, and providing feedback to policymakers.

Referring to the Northian distinction between formal and informal institutions, formal institutions are conceptualised as 'straightforward.[7] They are codified, traceable, and transmissible rules, usually written, and enforced by organised structures functioning independently (as third parties) within the state (legal systems) or as private entities (private arbitration courts). Examples of formal institutions are codes, declarations, constitutions, acts, resolutions, orders (company law, private property law, etc.), regulations, and contract systems.

By guiding/shaping human interaction and reducing uncertainty through providing structures to everyday life,[8] institutions allow human behaviour to be predicted more easily and thus reduce the costs of making transactions between people. Institutions are considered to be the basic determinant of the performance of an economy,[9] playing a decisive role in securing private property, enforcing contracts, maintaining public order and limiting the abuse of power, while stimulating human potential for technological innovation and investment, and allowing people to make best use of their talents and skills.[10]

Formal rules gained in significance as a result of the growing diversity of social and economic life, characterised by increasing specialisation and division of labour, and the development of long-distance trade and exchanges.[11] It became necessary to design structures for governing the making of transactions by institutions enforced independently (by third parties) within the framework of the law enforced by courts, protecting private property or concluded contracts. Institutions emerging on that basis were necessary when transactions were made outside of the sphere of the family, the local community or networks based on craft guilds or inhabited localities and it was impossible to enforce informal rules. Reducing uncertainty[12] and lowering transaction costs was decisive in strengthening the processes of cooperation and the making of transactions.

New Institutional Economics provides three key elements on which its cognitive view is based: transaction costs, property rights and contracts.

Transaction costs which accompany any transaction made are shaped depending on the character of the transaction made and on the institutional environment, including the political system, legal system, culture, educational system, etc.[13] The technological and institutional support necessary to complete the transaction generate costs, the amount of which forms the basis for looking for alternative ways of allocating property rights and organising transactions. Depending on the uncertainty accompanying the transaction, the specifics of the assets engaged or the frequency of the transaction, there are many different ways to organise the transfer of rights, depending on the cost of this transfer.[14] Property rights (rights to use resources) enforced by law (formal title of legal ownership) or de facto rights (property right based on a traditional form of ownership) have an influence on markets, companies and other organisations participating in production processes. Property rights have an impact on the scale of investment and innovation in the economy, as well as on losses resulting from damage to the natural environment. Contracts as mutual agreements reached between parties to the transaction determining the scope, transfer and enforcement of property rights structure and secure transactions in order to reduce transaction costs. They are tools used for the organisation of transactions and the governance of partners.

Institutions are important for economic outcomes, as they determine and enforce property rights through governance schemes. They structure stakeholder relationships, and, within the framework of contractual agreements, organising transactions and coordinating transaction partners, they have an impact resulting in more intensive cooperation in different combinations. The connection of the bioeconomy with Nature has a significant impact not only on the institution of agricultural contracts[15] and concerning primary production, but also conditions a broad set of relationships on which they may grow, also related to property law or possibilities of governance of partners.

From the point of view of transaction costs, attention is paid to the development of structures of governance as a result of entities seeking to lower the transaction costs of their cooperation. In the area of property rights, the criticality of which is determined by their scope and enforceability, attention will be devoted to rights to common pool resources, in order to outline the possibilities of avoiding excessive exploitation of the natural environment.

2.1.2 Ownership of common pool resources, transaction costs and costs of the application of governance structures under polycentric conditions

Issues of property rights in relation to the bioeconomy relate largely to the management of common pool resources, which involves the behaviour of economic entities that are tempted to derive individual benefits from exploring common pool resources in a way that contributes to the degradation of these common pool resources – that is, their destruction or depletion. The possibility of the phenomenon of "*the tragedy of the commons*" indicated by G. Hardin[16] sheds light on the destruction and depletion of natural resources under conditions of excessive exploitation by some users in a way that maximises their private benefits, while harming other users. Faced with the inevitability of the conclusions arising from Hardin's analyses, showing only the privatisation or nationalisation of common pool resources as possible institutional solutions, E. Ostrom advanced some strong sounding proposals, pointing to alternative possibilities of managing common pool resources, namely that they should be managed by the users of these resources themselves.

Research devoted to the management of commons is important for the analysis of relationships/dependencies in the circular bioeconomy, which is perceived from the perspective of structural changes entailing social adjustments, including those based on shaping attitudes to natural resources. The core of analyses conducted as part of research into the management of common pool resources is to focus on the possibility of deriving value from them for everyone under conditions when there is open access (in the sense of the absence of individual property rights) to scarce, naturally renewable resources. Common pool (or common property) resources can be used under the rules of exploitation created by their users – enforced by their own institutional solutions. However, Ostrom placed particular emphasis on the principle of conducting analyses of specific cases before determining the effectiveness of a possible solution.[17] It is of key importance for the adopted institutional solutions to take a number of conditions and determinants of individual situations into account, especially the possibility of users participating in the creation and enforcement of rules themselves.[18] Constituted on the basis of recognising the possibility of deriving benefits from common pool resources, the institution of ownership is focused on the rules of behaviour related to the deriving of value from resources, including: establishing rules; monitoring the conduct of resource users; subjecting them to sanctions for non-compliance with established rules, or on ways of resolving conflicts arising between users. Ostrom proposed a specific set of conditions that need to be met before property can be managed by a community. The full set of factors proposed by Ostrom upon which successful self-governing management of common property depends consists of clearly defined boundaries to common pool resources, transparency of applicable rules (adapted locally, to the specificity of the commons, and also in proportion to the obligations and benefits), co-creation of applicable rules, monitoring of applicable rules by community members or an external entity responsible to the community (best results achieved with internal monitoring), introducing graduated sanctions depending on the frequency of breaking the rules, implementing rapid access and low-cost conflict resolution mechanisms, as well as independence from state authorities, maintaining a system independent of the state's decisions, but approved by it, establishing rules of governance from the bottom up to ensure the congruence of all cooperation processes.[19] Ostrom drew attention to the beneficial impact of institutional diversity on identifying possible applicable solutions. She pointed to the need to look for appropriate solutions for individual cases, proposing a set of basic rules resulting from her analyses as support. Creating institutions in relation to common pool resources is a long-term process, the success of which requires ensuring coherence of individual elements of the systematically developed property institution. These institutions endure thanks to the impact of jointly adopted rules regarding (mutual) monitoring of the use of resources, sanctions for failure to comply with norms of established conduct or rules of inheritance of rights within the community. Recommendations resulting from research conducted into the need to maintain stability within a given community are important in order to ensure success of the implemented rules of effective management of common pool resources, in particular regarding the disruption of the co-creation of rules governing the use of common pool resources. The introduction of sanctions and methods of conflict resolution should remain coherent with the applicable law in a given country, along with such important pillars of the institution of common pool resources as the need to determine the boundaries of a common pool resource or the number of users of this resource.[20] However, shortcomings of the institution of managing the ownership of common pool resources may be revealed as a result of changes in the group of users of common pool resources or changes in the environment in which they operate.

In summary, seen through the prism of research into common property, it is possible to point out opportunities emerging in this area of drawing important conclusions as to how to solve problems of global use of natural resources and issues of stimulating economic growth ensuring sustainable development. These recommendations focus mainly on co-creating applicable rules for the use of common pool resources or responsibility to the community (monitoring and enforcement of established rules of conduct).

Transfer of the rights of ownership of the use of a resource (transaction) may take place within the framework of various organisational arrangements, among which institutionalists distinguish markets, hierarchies and hybrids. Independent of the adopted governance arrangement, transfers of rights (transactions) involve costs, which it is necessary to incur for the transaction to take place, in other words for the parties to the transaction to confirm their commitment. Costs perceived as such include the costs of searching for and informing the people that one wishes to deal with, as well as costs of negotiations, costs of drawing up of the contract and costs of monitoring.[21] They are perceived as a set of costs (of search, information, bargaining, decision-making, monitoring and enforcement), resulting from organising the market exchange.[22] Parties to transactions face complex contractual arrangements within competitive constraints and a variety of modalities through which parties can structure transactions. From this perspective, the role of transactions in the choice of individual arrangements for the governance of transactions (transfer of rights) is revealed. Differentiation in transaction costs is determined by differences in physical attributes, institutional factors or methods of negotiation and execution of concluded contracts.[23] Depending on the adopted organisational modalities (governance structures), the negotiation and execution of transactions may be perceived as a phenomenon occurring within an institutional matrix.[24] Williamsonian institutional matrices adopted for carrying out transactions are at the same time conditioned by frameworks defining individual/objective and other transfers in the economy.[25] Transactions are drafted, negotiated, implemented and conducted with a view to minimising costs through organisations as governance structures.[26] Organisations designate sets of possible modalities so that decision-makers can choose ways of governing the transfer or of exercising rights to products or services (in order to derive benefits from the division of labour). In choosing the method of transfer of rights, parties seek reduce transaction costs as much as possible, fixing a framework for action and restraining opportunistic behaviour in response to imperfect information and limited knowledge (with the help of contracts), or defining property rights. Williamson considers adaptation to transactional hazards through the provision of modalities as the main purpose of economic organisation.[27]

Under conditions for the functioning of the bioeconomy, special attention is paid to hybrid systems that combine the characteristic attributes of the market and hierarchy in various dimensions of analysis.[28] They require governance mechanisms, perceived as distinct for hybrids, for cooperation to be secured under conditions of partially shared rights.[29] Hybrid governance structures are defined by agreements to monitor shared rights among entities that remain legally distinct. While remaining autonomous, these entities cooperate/function together, operating through contractual agreements that provide a highly flexible framework to face unanticipated disturbances.[30] In addition to autonomy of parties as a fundamental determinant of hybrid governance arrangements, another important feature of hybrids is the use of arbitration instead of solving disputes through the courts. One particular property of hybrid modalities that is emphasised is the capacity of these governance systems to adapt[31] in the context of searching for alternative governance structures such as intermediary institutions or replacing short-term contracts with long-term contracts.[32] The occurrence of strategic alliances, joint ventures, franchising, consortia, networks, subcontracting, and public–private partnerships can also be considered in this light. Therefore, taking into account the existence of various modalities allowing parties to organise transactions, the conditions for the development of the bioeconomy are presented as opportunities for arranging exchanges conditioned by transaction costs resulting from physical attributes/characteristics, institutional factors and modalities of negotiation and enforcement,[33] the nature of people entering into contracts (opportunism, bounded rationality), the characteristics of the contracts themselves (the systematic nature of contracting, the uncertainty inherent in the contract, the level of specificity of assets necessary to be included in the contract[34]) in organisational structures created as part of the functioning of the bioeconomy. Additionally, it is worth taking into account that activities involving natural conditions (weather, climate change, etc.), including agricultural production, create opportunities for moral hazard (taking excessive risks or failing to exercise due diligence once insured, or under conditions of the promise of compensation of losses from public funds, and so on), limitations on possibilities of specialisation (relatively weak possibilities of exploiting benefits/economies of scale).[35]

The governance of almost all complex social or natural resource systems (e.g. resource depletion, decarbonisation, food insecurity) is polycentric, that is, it involves distributed, nested, and partially overlapping patterns of competitive and cooperative relationships among relatively autonomous private and public actors, operating at different levels, within a set of overarching rules. Polycentricity arises from the creation of various governance structures, in which it is presented as a combination of many centres of decision-making, which remain independent of each other, but at the same time create an interdependent system of relations.[36] The growing importance of cooperation networks and of multi-layered, local and decentralised activities are considered in the context of emerging polycentric systems in which actors follow different logics (state, community and market) and operate across different scales.[37] The institutional ground created by local communities is fertile for many innovative solutions that demonstrate the feasibility of alternatives to existing approaches, such as nature-based solutions,[38] living labs[39] or energy communities.[40]

Alongside the important role played by local institutions, institutional solutions operating at such scales of coordination as regulatory government agencies, international organisations, non-governmental organisations of various sizes and influence, associations, farmers, processors, brokers and educational institutions play an important role in the governance of natural resource systems, including within self-organising orders. Existing institutional solutions may be characterised by a greater or lesser degree of polycentricity. Polycentricity is a theoretical construct with institutional attributes capable of producing and providing products and services necessary for a given community or of unleashing entrepreneurial potential in the pursuit of securing the interests of given social groups. Such a governance system is structured to give actors opportunities for institutional innovation and adaptation through experimentation and learning (between local user groups, government officials, etc.).[41] Within the framework of processes of adaptation taking place in individual governing structures, rules are created and adapted that are specific to a given community and must be followed by members of that community, increasing the chances that they will be effective in the management/use of natural resources. A high degree of polycentricity of the system is indicative of its high degree of complexity and adaptability, and the lack of a central authority exercising a dominant function over the entire system. It is expected, in reality, that suboptimal results will be achieved, especially in complex and multi-layered structures. Increasing the degree of polycentricity is justified by exhaustion of the possibilities of adaptation that may result from basing the system only on centralisation or only on decentralisation and the need to stimulate the potential flowing from various/multi-scale institutions in order to more effectively combine local knowledge and experience with scientific knowledge[42] so as to generate an appropriate solution to an important problem. Design and adaptation of institutions at multiple scales and their generation of information allows participants in the system operating at many different scales to learn from experience (able to deal with more complexity than any single corporate entity can absorb and manage).[43]

An analysis of polycentric systems/arrangements/schemes/structures involves research into the conditions conducive to the development of adaptive systems in which each participant has a certain degree of autonomy to deal with some set of political problems. As part of such analyses, it is assumed that systems of governance are more efficient when citizens and are able and empowered to self-organise than many government bodies at different levels of scale. Moreover, the self-government of social groups is considered to be one of the basic attributes for designing any institutional structures/schemes on a broader scale (contributing to regional and national policy or consulting legal powers at constitutional level).

In summary, imperfections are noted in the ability of private entities to build systems to solve social problems based on biophysical or economic determinants of the condition of life (education, health). At the same time, there is much evidence that the strength and multilateralism of state power are indispensable in securing the efficient functioning of the market (competition law, conflict resolution, etc.). The many expectations placed on territorial representation in relation to transnational problems have turned out to be unjustified due to the exhaustion of many mechanisms of action at this level of scale. Some authors attempt to point to the role of clubs and networks in the process of reformulating regulations or competition rules. The emergence of networks of functional integration conducive to the initiation and development of institutional structures of cooperation and for the sanctioning of norms of common conduct in order to secure collective order in pursuit of common goals creates a space for searching for solutions worthy of analytical attention. *Formal rules are given stability by supportive informal institutions, which have tenacious survival ability because they have become part of habitual behavior*.[44] Social and economic organisations acting within the system of incentives defined by the institutional framework perceived as forcing a change in behaviour by changing formal institutions (the defining of institutional frameworks in terms of formal rules) leads to changes in informal rules. Initiating changes by formally enforcing behaviour may influence society's perception of certain attitudes/habits/customs over time and may determine the decisions they make on an individual and collective level (e.g. the necessity to segregate waste under penalty of punishment leads people to form habits in the decisions they make in their further everyday lives). By influencing the profitability of making transactions, as well as the organisation's ability to increase efficiency from specialisation/the division of labour or by defining the frameworks within which organisations operate, including facilitating the adoption of new technologies in the economy, institutions influence economic results.[45]

Among the conditions of the bioeconomy, the role of not only cooperation, but also competition between various administrative units (state, local government – both in the territorial and professional spheres, and local/civic and educational authorities, etc.), which give these areas of economic governance their polycentric features and attribute certain consequences to them, is particularly important. However, polycentricity as a system for decision-making between formally independent centres of power may also take the form of an interdependent system of relationships.

2.1.3 Informal institutions for the bioeconomy – a cultural mindset

Culture can be defined as *those customary beliefs and values that ethnic, religious, and social groups transmit fairly unchanged from generation to generation*.[46] Such a narrow approach focuses on those dimensions of culture that influence the shape of the economy and economic outcomes. Although culture has not entered the mainstream of economic research, numerous works, starting with the classics, have shown its influence on the economy: from A. Smith and J.S. Mill, to the works of M. Weber, A. Gramsci, E. Banfield and K. Polanyi, and to contemporary analyses by D. Landes, F. Trompenaars, R. Barro and many others. The circular bioeconomy can be seen as the next stage of evolution (see Figure 2.4), whose aim is to replace a fossil fuel-based economy with one based on renewable biological resources and knowledge.

The way we use natural resources is the result of the evolutionary process of cultural phenomena, especially in the field of values – for example, attitudes towards nature; and in the field of practices – for example, agronomy and agriculture.[47] The cultural roots of the environmental crisis were already described in the 1960s by Lynn White who identified giving value to an anthropocentric view and sanctioning an exploitative treatment of nature as being attributes of Judeo-Christian heritage.[48] Jacques Attali described the heritage of religion as a reservoir of values that have evolved in society, and presented Judaism as the first modern religion to give value and meaning to the contract – as exemplified by the covenant made at Mount Sinai, as well as to personal freedom, private property, work and wealth, while demystifying the world and nature and making them a resource for exploitation. These values have largely permeated Christianity, especially Reformed Christianity. Here it is impossible not to refer to Max Weber's work *The Protestant Ethic and the Spirit of Capitalism*, in which the author posits that the values created on the basis of the development of the religious system directly contributed to the emergence of industrial capitalism, thanks to the strengthening of individualism, ethics and the work

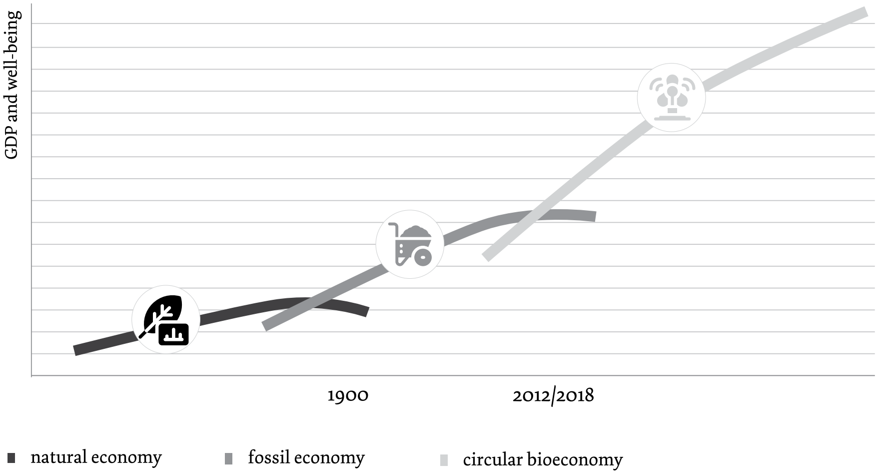

Figure 2.4 Evolution of the economic order.

Source: Own elaboration, based on Sustainable growth from bioeconomy. The Finnish Bioeconomy Strategy, 2014, https://www.bioeconomy.fi/facts-and-contacts/the-finnish-bioeconomy-strategy/

ethic. Protestantism, which places special value on saving, sees getting rich as a manifestation of God's favour. Paradoxically, Protestantism, whose aim was to restore traditional Christian values and return to the simple life of the early Christians, contributed to the secularisation and modernisation of Western civilisation. 250 years ago, with the outbreak of the first Industrial Revolution, individual initiative, capital accumulation and progress, including technological progress, became the driving force of economic development and set the world (especially Western civilisation) on the path of endless expansion in science, technology, production and trade, population, etc. and thus propelled it into the age of modernity.

The values of the new era, along with technologies and access to non-renewable resources, have brought wealth and material security to billions of people, but the progress of modernity has set its own limits,[49] which are both broken planetary boundaries and a stagnation, sooner or later, in the perception of the quality of life, life expectancy or happiness.[50] Jonas and Jonatan Salk wrote in 1981:

> *We are on a frontier, but it is not territorial or technological; it is human and social. In this period of changing conditions and values (…) We will, in the process of responding to forces and limits of nature, learn whether we have the capacity to meet this challenge. If we do, then we will emerge from the present period not merely as survivors, but as human beings in a new reality.*

According to the Salks, population development and thus socio-economic development follows an S-shaped curve (Figure 2.5).

In the first part of the diagram, population growth accelerates; in the second part, growth slows down and a plateau is reached. The turning point is the moment of transition from accelerated growth to decelerated growth. These

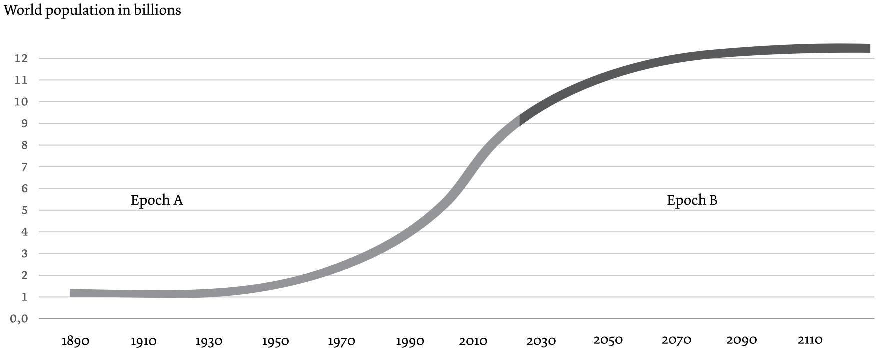

Figure 2.5 S-shaped curve of the socio-economic development.

Source: Own elaboration based on: J. & J. Salk, 2018, *A New Reality. Human Evolution for a Sustainable Future*, City Point Press, Canada and J. & J. Salk, 1981, *World Population and Human Values: A New Reality*, HarperCollins, New York.

two periods can be characterised by different attitudes and values. In epoch A, the initial phase of growth, the focus is on quantity, competitiveness, strength, independence and overcoming external constraints. In epoch B – the slowdown of population growth – a shift in the hierarchy of values towards quality, cooperation, interdependence, consensus and self-restraint is expected. The assumptions of the circular economy, the bioeconomy, the social economy and other manifestations of sustainable development correspond to the values of epoch B and the shift from materialistic priorities to social priorities and those related to the self-realisation of the individual. Are we really witnessing and participating in this form of progress? This hypothesis is partly confirmed by research on changes in values. The World Values Survey (www.worldvaluessurvey.org) initiated by Ronald Inglehart, which spanned several decades, enabled him to formulate a thesis on the evolution of values from materialism to post-materialism, which can be observed above all in highly developed societies. Similar conclusions were reached by Roy and Anderson, who, in their book *Cultural Creatives*, presented the evolution of values of individuals in highly developed societies starting from the Traditional level, which is followed by the Moderns and then the Cultural Creatives. Table 2.1 provides a comparative list of characteristics.

The evolution of social values observed by Inglehart and Ray seems to be a necessary precondition for a change in attitudes towards production and consumption and the introduction of the sustainable development paradigm. In addition to this change, awareness and understanding of what a circular bioeconomy is, societal acceptance of these assumptions and willingness to cooperate are also required. While a noticeable change is taking place in

Table 2.1 Comparison of the values of epochs A and B

		Ronald Inglehart: post-materialism: key values		*Roy and Anderson: cultural creatives: key values*
Epoch A	Materialism:	Material values and material success, sense of social security, conformism, moral traditionalism, discipline, authority, hierarchy, social and economic domination of men, search for certainty in the face of existential questions	The Moderns	Success, economic values, technological progress, money, efficiency, speed, linear analysis

(*Continued*)

Table 2.1 (Continued)

		Ronald Inglehart: post-materialism: key values		*Roy and Anderson: cultural creatives: key values*
Epoch B	Post-materialism:	Non-material goals such as self-expression, autonomy, freedom of speech, gender equality and environmentalism, possibility of self-realisation and self-expression, autonomy, diversity, loss of trust in religion and authority, need for agency, secular customs, individualism, search for the meaning of life	The Cultural Creatives	Planet, ecology, human rights, civil liberties, personal growth, 'authenticity', synthetic way of thinking

Source: Own elaboration based on Ray, P., Anderson S. R., 2001, *The Cultural Creatives: How 50 Million People Are Changing the World*, Crown, New York; Inglehart, R., 2016 (1977), *The Silent Revolution: Changing Values and Political Styles Among Western Publics*, Princeton Legacy Library.

Western society at the level of values, creating awareness of the bioeconomy is a challenge. Low awareness of bio-based products, especially among end-consumers, and a lack of skills and relationships on the part of producers are cited as among the biggest barriers to development of a bioeconomy,[51] along with openness, willingness to engage in dialogue and civic engagement. The involvement of citizens who are also consumers is crucial not only for raising awareness but also for the acceptance of bioeconomy regulations and policies.[52] Knowledge about the extent of the bioeconomy among European citizens is very patchy. However, research is increasingly beginning to paint a relatively coherent picture of the state of play. Table 2.2 summarises selected research findings analysed in terms of self-assessed awareness and basic associations.

In the context of the above-mentioned studies, which consider European countries, the respondents show a relatively high level of awareness of the bioeconomy and bio-based products. Nevertheless, the above-mentioned associations demonstrate the lack of accurate knowledge and information. It should be emphasised that the associations with the bioeconomy are predominantly positive, which is important from the perspective of its dissemination. However, a large part of the population interviewed does not associate the bioeconomy with a future functional model of economic reality, a manifestation of the

Table 2.2 Overview of research results on bioeconomy awareness in European countries

Author and year	*Declarative awareness/ knowledge of bio-based products/ bioeconomy*	*Associations*	*Study countries/ sample size*
Veldkamp. 2013	8% (have heard about the bioeconomy)	Sustainable development, nature, economy, ecology	Netherlands, n = 1553
Meeusen et al., 2015	Denmark 54% Germany 73% Italy 93.5% Netherlands 41.5% Czech Republic 84.5% Slovenia 98.3%	Recyclable, organic, natural	Denmark, n = 1012 Germany, n = 1136 Italy, n = 1060 Netherlands, n = 1016 Czech Republic, n = 1008 Slovenia, n = 1011
Sijtsema et al. 2016	36%	Biotechnology, biofuel, organic, biodegradable, environmentally friendly	Denmark Germany Italy Netherlands Czech Republic Total, n = 89
Delioglanis and Tzagkaraki, 2018		Biotechnology, biofuel, organic, biodegradable, environmentally friendly	UK, Belgium, Netherlands, Sweden, Denmark, Estonia, Lithuania, Czech Republic, Austria, Italy, Bulgaria, Greece, Spain, Portugal, Total n = 452
Blesin and Klein, 2017	43%	Environmental protection, biodegradability, raw materials, recycling, organic products	Germany, n = 1673
Stern et al., 2018		Bio-based products, organic farming, sustainability, no answer	Austria n=456,
Filho et al., 2021	35% (awareness of bioplastics)		16 European countries, n = 127
Notaro & Paletto, 2021	81% (awareness of bio-based textiles)		Italy, n = 1000
Gaffey et al., 2021	50% (awareness of bioplastics)		Ireland n = 500 and Netherlands n = 500

(*Continued*)

Table 2.2 (Continued)

Author and year	*Declarative awareness/ knowledge of bio-based products/ bioeconomy*	*Associations*	*Study countries/ sample size*
Kymäläinen et al., 2022		Organic, natural, ecological, recyclable	Finland, n = 47
Pink et al., 2024	80% (awareness of the bioeconomy)	Sustainable development, ecology, bio-based products, agriculture	Poland, Czech Rep., Spain, Portugal, n = 370

Source: Own elaboration.

evolution of the production approach, but, rather superficially, perhaps through the prefix 'bio-', with aspects of ecology, environmental protection, ecological production, naturalness, etc. What is also puzzling is the rather uncritical evaluation of this phenomenon. Respondents rarely express doubts about the bioeconomy, which can also be associated with unsustainable exploitation of the natural environment. In the field of shaping conscious choices of consumers, producers and other stakeholders, the concept and perception of the bioeconomy may still be one of the biggest challenges in its sustainable implementation. Christian Patermann and Alfredo Aguilar[53] formulate a list of the most pressing challenges facing the bioeconomy in the third decade of the 21st century, which includes: enhancing its social impact; extending its reach beyond academic and elite circles; establishing links with society at large beyond those already in place with academia, industry and financial markets; ensuring that the bioeconomy promotes responsible and sustainable production of bio-based products along with responsible consumption; and organising a forum to discuss a relevant framework for ethical issues and governance. These are problems whose solutions can be created at the level of formal institutions, but both their origin and their solution lie in the realm of values, awareness and willingness to create links, including informal ones, between actors in the.

Notes

1 For the sake of simplicity, Figure 2.1 does not include links related to product logistics and shows a rather complex institutional environment. The graph uses examples of two types of biomass: wood and sugar beet. They are cascaded to allow them to realise their full potential. Wood obtained for the production of furniture is a source of by-products in the form of cuttings, chips, wood dust, which can be used to produce cellulose, paper and fabrics (e.g. Tencel). The resins and proteins contained in wood can be raw materials for the production of plant protection products, cosmetics (resins) or fish food (protein). Of course, these examples do not exhaust the list of possibilities. At each stage of use, by-products can also be used

to produce fuel, energy and compost, which completes the cycle. Sugar beet can be used for its original purpose, but it also feeds the value chain with by-products – molasses, pulp, etc. Sugar beet can also be used to produce chemicals and biopolymers. As in the case of wood, by-products generated at each stage of processing constitute an energy raw material and a base for compost.

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3 Bioeconomy policies

From global to local perspectives

Ondřej Konečný, Alice Kozumplíková and Radka Redlichová

3.1 Introduction

Systematic policy attention to the bioeconomy began to increase after 2010, but bioeconomy policy can be linked to discussions on sustainable development, renewable resources and the fight against climate change over the last two to three decades. In the last two decades, bioeconomy strategies have become more widespread and have begun to occupy a more prominent place in the policy agendas of national and international organisations. It has become a global tool and part of global development, for example in the framework of the United Nations and its Sustainable Development Goals (SDGs). Based on a bibliometric analysis, Gould, Kelleher and O'Neill[1] argue that the bioeconomy as a policy and research concept is relatively new but still evolving, with European countries (especially in Northern and Northwestern Europe) leading the way. The European Union (EU) adopted its first bioeconomy strategy in 2012, known as 'Innovating for sustainable growth: an EU bioeconomy strategy'. This strategy was updated in 2018, when a new framework, called the 'Updated Bioeconomy Strategy for Europe', was introduced. In the US, the bioeconomy has been part of the science and technology agenda since the beginning of the 21st century. Several federal agencies, including the Department of Agriculture and the Department of Energy, have programmes focused on the bioeconomy. Even from this shortlist, it is clear that different countries and regions have different approaches to bioeconomy policy, depending on their specific needs, natural resources, and economic and social goals. It is therefore important to note that definitions and policy objectives of the bioeconomy may vary depending on the specific geographical and socio-economic context.

Bioeconomy policies are based on strategies, regulations, initiatives and action plans, which aim to support the sustainable use of biological resources for balanced economic and social development. It is therefore logically a multidisciplinary approach that seeks to integrate a range of sectors such as agriculture, forestry, fisheries, food, biotechnology or renewable energy into a coherent framework that supports sustainability, innovation and competitiveness. According to Gould, Kelleher and O'Neill,[2] bioenergy and forestry are the most common policy areas. In the analysis of regional strategies by Haarich

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and Kirchmayr-Novak,[3] one-third of the sectors addressed in the strategies relate to the supply side, mainly agriculture and forestry, but also organic waste. Another third of the sectors addressed relate to the processing and conversion of biomass, often associated with bioenergy and biofuels, the agro-food sector or the construction industry. Only a few bioeconomy strategies focus on increasing the added value of the bioeconomy sector, while some, mostly fully specialised strategies, address all steps of the bioeconomy value chain. Depending on the sector, key bioeconomy policy objectives often include:

- Increasing the production and use of bio-based products and bioenergy.
- Ensuring food and energy security.
- Support for research and innovation in life sciences and technologies.
- Development of sustainable supply chains.
- Improving the management and protection of natural resources.
- Reducing the impact of human activity on the environment and mitigating climate change.

Haarich and Kirchmayr-Novak,[4] in their study of regional strategies to support the bioeconomy, show which policies are most commonly applied in practice to support the bioeconomy. Research and innovation funding and management are the most frequently mentioned (Figure 3.1). These policies are found in regional strategies across Europe. The governance measures included aim to ensure policy coherence across sectors, actors, levels of governance and timeframes. The policy strategies vary in scope and depth, have different objectives and address different actors that will play a crucial role in supporting the development of the bioeconomy. Collaborative policies, whether facilitating bottom-up initiatives or enabling multi-stakeholder engagement and dialogue, are present in a large proportion of these documents. Other important policy measures, which are less frequently mentioned, include: promotion measures to raise awareness and provide information about the bioeconomy; infrastructure, i.e. support for bioeconomy research centres (or units) and pilot and demonstration facilities; education measures; and support for demand stimulation (including new legislation, public procurement, and branding, certification or standards).

Just as in the case of bioeconomy policy, where it is necessary to think about a broad framework of affected areas, the same also applies for the list of relevant actors that are important within the bioeconomy. Governments and representatives of transnational territorial entities are most often identified in the literature as key actors in supporting the sustainable development of the bioeconomy. By adopting bioeconomy-related policies, they create the basis for political support and investments that enable cutting-edge research, facilitate the development of new and advanced technologies, support the development of human resources, accelerate commercialisation processes and meet demand.[5] However, individual actors within the bioeconomy do not have a comparable position. Lühmann[6] concludes that some strategies favour industry and research actors and largely

Policy strategies and guidelines

Framework Strategies: framework strategies for the bioeconomy that set out guidelines and targets to promote the sustainable use of biological resources.
Climate and sustainability commitments: integrating targets into broader strategies (e.g. Sustainable Development Strategy).

Financial support

Research, innovation sector programmes: funding for projects focused on the bioeconomy, for example in the fields of agriculture, forestry, water and biotechnology.
Regional and Cohesion Funds: these provide funding for regional development, including bio-economic projects.

Research and innovation

Joint Technology Initiatives and Partnerships: creating partnerships between academia, industry and government to foster research and innovation in the bioeconomy.
Networks and clusters: support the creation of networks and clusters that connect different actors in the bioeconomy ecosystem, thereby increasing innovation potential and improving market access.

Regulatory measures

Standards and certification: developing and implementing standards and certification systems that ensure the sustainability and quality of bioeconomy products and services.

Education and awareness

Awareness campaigns and information services: various awareness-raising and information events aimed at raising awareness of the importance of the bioeconomy.
Training programmes: support the development and updating of training programmes that focus on the skills needed for the bioeconomy sector.

Figure 3.1 Conditions for the development of the bioeconomy.

Source: Own elaboration.

ignore the views of agricultural associations and (forestry) NGOs. Park and Grundmann[7] therefore argue that it is very important to understand how the inclusion of primary producers, a relatively marginalised group in the bioeconomy narrative, is framed and legitimised in related policy discourses and how these change over time. At the same time, it must be added that, while scientific innovation and research are important for the bioeconomy, so too is social acceptance and engagement, and a supportive and coordinated policy environment across sectors, including agriculture, climate, employment, energy, environment, fisheries, forestry, international cooperation, materials, rural development, social inclusion, trade and transport. Specific territorial contexts mean, of course, that policy support and approaches to the bioeconomy will differ between countries, regions and localities, as will their dimensions and impacts.

3.2 Environmentally-targeted policies and interdependencies with bioeconomy

Bioeconomy policies are strongly anchored in environmental policy documents. Environmental policies and instruments play a key role in global efforts to protect the environment and achieve sustainable development. Indeed, bioeconomy policies contribute to building a bioeconomy that addresses all three dimensions of sustainability:[8]

- Environment: management of land and biological resources within ecological boundaries;
- Economy: sustainable value chains and consumption; and
- Society: social justice and just transition.

For example, the EU has set ambitious goals in the area of sustainability, food security, reducing pressure on natural resources and dependence on fossil fuels, which are accompanied by many challenges and strategic steps. One of these strategic directions is to support the bioeconomy, which has become an important part of the broader framework for achieving sustainability and circularity in the European economy. Through its policies and instruments, the European Union is seeking to meet the Sustainable Development Goals for the period 2015–2030, which translate directly into the European Green Deal strategy (Figure 3.2).

It is within the framework of these principles that the idea of the bioeconomy has been promoted in the EU. The development of the bioeconomy is reflected in the European Bioeconomy Strategy, which aims to accelerate progress towards a circular and low-carbon economy. The strategy aims to modernise and strengthen EU industry, creating new value chains and greener, more cost-effective economic processes. At the same time, it aims to protect and promote biodiversity and all other components of the environment.[10] It is in this spirit that the promotion of the bioeconomy is being implemented, which is currently an important theme within the evolving policies and instruments being formulated and applied within the framework of the Green Deal for Europe. These policies aim to guide the EU towards an ecological transformation with the ultimate goal of achieving climate neutrality by 2050. The bioeconomy can be an instrument for implementation and support in practically every area of the Green Deal, and this is how it is treated at the level of European strategies (Table 3.1).

Although the bioeconomy is one of the instruments for implementing each of the Green Deal objectives, it is particularly strongly interconnected with other European strategies, including agriculture, energy and circular economy (Figure 3.3). The implementation of the bioeconomy is supported by 15 Green Deal initiatives:

- Adaptation Strategy
- Biodiversity Strategy
- Chemicals Strategy for Sustainability
- Circular Economy
- European Climate Law
- Farm to Fork Strategy
- Forest Strategy

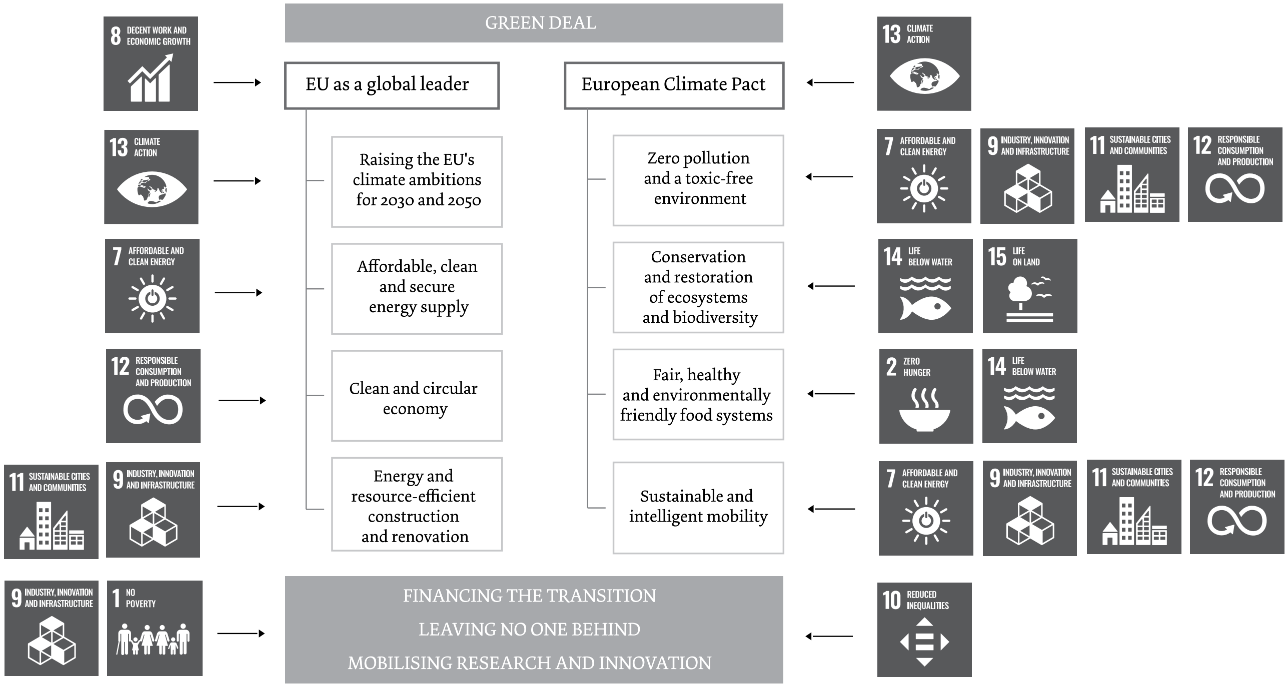

Figure 3.2 Policy areas of the European Green Deal in the context of Sustainable Development Goals.[9]

Source: Own elaboration.

Table 3.1 The importance of the bioeconomy for the Green Deal

Main Green Deal objectives	*Bioeconomy impact*
Increasing the EU's climate ambition for 2030 and 2050	The process of capturing carbon in soil, marine environments (known as blue carbon), and forests, alongside storing it within harvested wood products, along with substituting fossil-based items like plastics, energy, and textiles with sustainable alternatives, holds the potential to deliver substantial carbon reductions. These actions can help achieve the target of a 55% decrease in emissions by 2030.
Supplying affordable, clean and secure energy, and building and renovating in an energy- and resource-efficient way	Biowaste can be converted into energy, including biofuels for sectors in which electrification will remain challenging (aviation, maritime).
Mobilising industry for a clean and circular economy	Circular utilisation of biomass enhances the efficiency of resources and encourages the creation of valuable products from surplus and discarded materials. Wooden, agricultural and food biowaste can be transformed into innovative biomaterials – bio-based composites, bioplastics and others.
A zero pollution ambition for a toxic-free environment	The circular bioeconomy optimises the utilisation of excess and leftover materials from agriculture, food processing, and forest-based industries, effectively decreasing the volume of waste sent to landfills. Additionally, employing bio-fertilisers, bio-pesticides, and natural pest control methods can aid in meeting the objectives outlined in the Farm to Fork and Biodiversity strategies. These methods aim to reduce the reliance on conventional fertilisers and pesticides while mitigating associated risks.
Preserving and restoring ecosystems and biodiversity	Advancing sustainable bioeconomies has the potential to boost biodiversity and enhance the delivery of vital ecosystem services.
A fair, healthy and environmentally-friendly food system	The circular bioeconomy combats food waste by transforming it into various valuable products, contributing to added value across multiple sectors. Furthermore, algae cultivation presents a fresh opportunity for generating renewable biomass utilised in both food and eco-friendly goods. This sustainable method offers the benefit of potentially high output without relying on extensive land or fertilisers, thereby promoting biodiversity.
Sustainable and smart mobility	Use of ethanol made from agricultural residues, such as wheat straw, in the transport sector can achieve up to 95% emission savings compared to fossil fuels.

Source: Own elaboration, based on European Commission.[11]

- Industry Strategy
- LULUCF (Land use, land use change and forestry)
- New European Bauhaus
- Renewable Energy
- Renovation Wave
- Sustainable Carbon Cycles
- Sustainable Financing
- Zero Pollution Action Plan

Therefore, the bioeconomy has a potential direct impact on climate change mitigation, which is seen as a key element in achieving climate neutrality and environmental, economic and social sustainability.[12,13,14] It focuses on the production of renewable biological resources and their transformation into value-added products such as food, feed, bioproducts and bioenergy. Supporting the bioeconomy can thus contribute to achieving the objectives of the EU's 'Fit for 55' climate package and the Farm to Fork Strategy.[15] In particular, it can contribute to reducing greenhouse gas emissions by reducing the environmental and climate footprint of the entire EU food system. Nor can we neglect the related requirements of the transformation of European forestry, which is necessary to conserve and restore the biodiversity of forest ecosystems and to tackle the climate crisis.[16]

These objectives are also included in the framework of the Common Agricultural Policy (CAP 2023–2027). The CAP is a set of instruments for managing agricultural and rural activities and has several key elements related to the development of the bioeconomy. The bioeconomy is reflected in the CAP as part of the support for the use of bioenergy in agriculture and forestry.

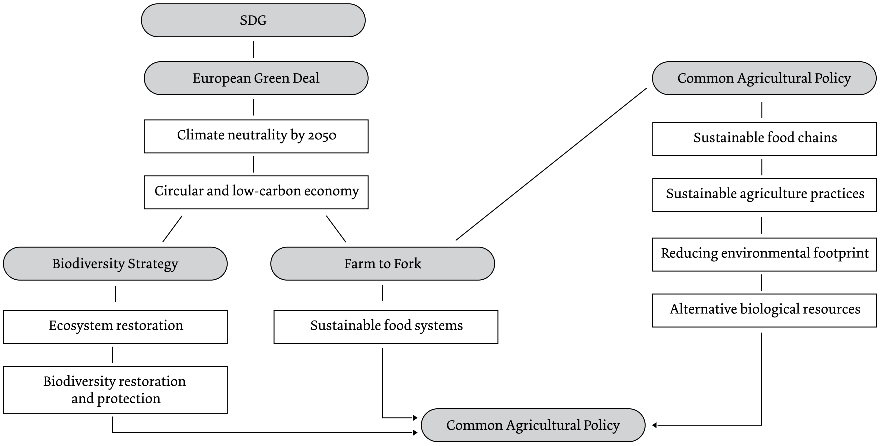

Figure 3.3 Relationship between selected strategies for implementing Sustainable Development Goals.

Source: Own elaboration.

The objectives of the CAP are implemented in the EU's rural development policy, which includes measures to support the production and use of renewable energy in rural areas by promoting environmental standards and agri-environmental practices in agriculture and forestry.[17] In addition to the CAP, the EU Biodiversity Strategy to 2030[18] plays a prominent role in the framework of environmental policies and instruments related to the bioeconomy. The strategy is part of the 'Farm to Fork' package of the Green Deal for Europe, which aims to contribute to synergies between the agricultural sector and the protection of biodiversity.[19]

The goals of the bioeconomy and those of the EU Biodiversity Strategy for 2030 can be mutually supportive in sectors and services related to the production, use, processing, distribution or consumption of biological resources. This applies to both agriculture and forestry. In particular, it can involve the restoration of degraded ecosystems, the promotion of sustainable supply chains, the protection of wetlands and marine ecosystems, and the sourcing of alternative biological resources for industry and business.[20]

However, the implementation of the Common Agricultural Policy (CAP) and European Green Deal (EGD) policies and instruments alone may not be sufficient to support biodiversity. Overall, biodiversity in agricultural and forest habitats is declining despite significant CAP intervention. The Birds and Habitats Directive Status and Trend Analysis (BHD habitats and species) for the period 2013–2018[21] shows that the majority of agricultural habitats have unfavourable status and declining trends compared to other non-forest terrestrial habitats. One of the main problems is that, despite efforts to integrate the principles of sustainability and biodiversity protection into these policies, there are still significant challenges and obstacles. The scientific community, supported by civil society, criticised the previous CAP for providing financial support to industrial agriculture (using fertilisers and pesticides), mainly in the form of direct area payments, without much emphasis on agri-environmental measures. Rather, these interventions led to inefficiencies by promoting fragmentation rather than cooperation between actors in biodiversity conservation.[22,23] Furthermore, Žáková, Krupová et al.[24] find, based on biodiversity index calculations, that agricultural subsidies have a limited effect on agricultural biodiversity (crop diversity), but a positive effect on land use diversity (especially for larger farms). A study by Scown et al.[25] confirms that CAP spending has exacerbated income inequality in agriculture, while little money has been allocated to support climate- and biodiversity-friendly agricultural practices.

In the newly introduced CAP (2023–2027), more responsibility is given to member states to formulate their own strategic plans according to EC guidelines, including the inclusion of agri-environmental measures to support biodiversity. However, according to Langlais,[26] the new CAP lacks a clear objective and a common model. According to the author, the term 'agro-ecological transition' is missing from the CAP documents, the timeframe of the desired agro-ecological transition is not defined and therefore it is not possible at present to determine what changes it will lead to. There is a need for a synergistic combination of agroecology and systemic intensification of agriculture, to optimise the provision of ecosystem services and address the challenges of the transition to more sustainable agriculture in terms of the environment and social equity. The challenge remains to design integrated land-use systems that combine both systems and optimise the provision of ecosystem services.

The strong element of EU bioeconomy policy initiatives is the Energy Union. The Union was launched in 2015 with the aim of reducing dependence on imports of energy commodities and energy and ensuring secure and clean energy. The goal is to achieve at least 40% renewable energy in the EU by 2030. Bio-based energy still has a key role to play here (see Figure 3.4):

- Biomass: for energy (bioenergy) is the main source of renewable energy (60%) in the EU. The heating and cooling sector is the largest end-user, using about 75% of all bioenergy.[27] The main source of biomass is forestry – logging residues, wood-processing residues, fuelwood, wood pellets etc.
- Biofuels: liquid or gaseous transport fuels, such as biodiesel and bioethanol, made from biomass.
- Biomethane: purified version of biogas, produced from the breakdown of organic matter.

It is worth emphasising the need to strictly comply with the assumptions related to the sustainable production of resources. Even though the directive states that biomass must be produced in a sustainable way, at every stage – from the growing of feedstock to final energy conversion – in practice, the use of forest resources may lead to irregularities. A good example of the risks associated with the unsustainable utilisation of forest biomass is a case study from Poland. Since Poland joined the EU, the amount of wood burnt in the energy sector has increased 140-fold – from 35,000 to ^{m3} to 4.9 million m^3. Woody biomass has become the largest renewable energy source in Poland. About half of the wood obtained from Polish forests is burnt as an energy fuel – directly or in the form of waste. One of the reasons for the growing share of wood in energy production is the possibility for Poland to fulfil EU requirements regarding the production of energy from renewable energy sources. The growing demand for energy wood is also fuelling the import of this fuel from abroad. In the period 2010–2020, imports increased by 917%, reaching 2.19 million tonnes in 2020. The wood-processing industry has been warning for several years that it cannot buy enough wood from the state forests. Meanwhile, the largest Polish power plants using wood biomass burn the equivalent of several hectares of forest every day[30] (Kolbusz, Mikos, 2022). The recognition of wood as a renewable energy source and its equation with other renewable energy sources was controversial due to the high level of emissions during combustion and the highly controversial approach to the value of the wood obtained, which is not fully utilised and burnt. On 9 October 2023, the Council of the European Union, albeit without Poland's support, adopted the final version of

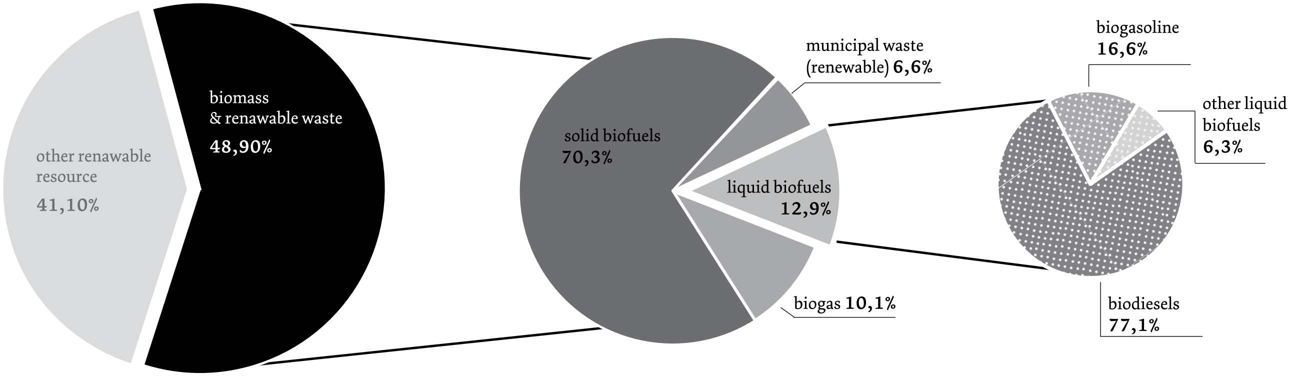

Figure 3.4 Bioenergy and biofuels as a percentage of renewable energy 2021.

Source: Own elaboration based on: EC.[28,29]

the revised Directive on the promotion of the use of energy from renewable sources (Directive (EU) 2023/2413 Of the European Parliament and of the Council). Restrictions were introduced on the use of forest wood for energy purposes:

- Moving away from subsidising and including energy from the burning of: Roots and stumps, wood useful for the wood-processing industry, and wood harvested from the most valuable forests (including ancient forests, virgin forests, wetlands) to meet renewable energy targets.
- Move away from subsidising the burning of biomass in energy plants that only generate electricity (with some exceptions).
- Obligation for member states to ensure that the use of wood for energy purposes does not conflict with targets for carbon dioxide absorption by forests. The amendment to the Directive was an important step towards harmonising energy policy with biomass. This case shows that without a clearly defined framework, the bioeconomy will not be a tool for sustainability, but will help to change the direction of resource exploitation.

The first Circular Economy Action Plan was presented by the European Commission in 2015 to support Europe's transition to a circular economy, strengthen global competitiveness, promote sustainable economic growth and create new jobs. It was adopted 5 years later. At the same time, other goals were crystallising that relate to reducing dependence on non-renewable raw materials, protecting the environment and biodiversity and making savings for consumers. The bioeconomy is a key area of the circular economy, complementing cycles based on non-renewable resources with cycles based on renewable (primarily) bioresources (see: https://www.ellenmacarthurfoundation.org/circular-economy-diagram). This understanding of the circular economy, which includes inherently circular renewable resources, was adopted by the European Commission, and funds for financing the bioeconomy were also included as part of activities supporting the transformation towards the circular economy. The European Investment Bank (EIB) injected EUR 65 million into the European Circular Bioeconomy Fund, marking the first equity fund solely dedicated to the bioeconomy and circular bioeconomy across the European Union and Horizon 2020 countries. This fund's objective is to offer financial support to pioneering companies and projects in their growth stages.[31]

To summarise, the EU Bioeconomy Strategy was born out of the need to improve the instruments for implementing the Sustainable Development Goals. It is part of the structure that supports other strategies within the European Community and, at the same time, promotes their dissemination and implementation. The mentioned strategies do not exhaust all the policy connections of the institutional environment, but they do highlight the density of the framework for the development of the bioeconomy and its importance for the direction of development of the European Union. However, this is an area that is strongly related to the geographical location, the potential of renewable natural resources and socio-economic phenomena that characterise individual countries and regions, such as the level of innovation. This means that the bioeconomy and the development of bioeconomy strategy vary widely across Europe and globally.

3.3 Bioeconomy policies across the world

Policy actions that can significantly contribute to the promotion of the bioeconomy and provide the basis for the establishment of new bio-based industries can be implemented at the regional, national, transnational or global level. Although there is no global strategy for the bioeconomy, the concept of Sustainable Development Goals provides a logical basis and foundation for subsequent strategic documents. Transnational documents are in line with it and already primarily target the development of the bioeconomy sector, such as the bioeconomy strategy of the EU. The transnational level is also represented by some cross-border initiatives, such as BIOEAST. These then provide the framework or impetus for national initiatives, which are followed by bioeconomy development strategies at the regional level (Figure 3.5). Such strategies then include the implementation tools mentioned in the introduction of the chapter.

As reported by Fund et al.,[32] the term bioeconomy has gained prominence in policy documents and strategies worldwide. However, definitions and understandings of the bioeconomy still vary in scope and focus. At the same time, new terms and concepts continue to emerge:

- *In Finland and in Canada, the concept of the (sustainable) "forest-based bioeconomy" has been defined.*
- *In the European Union, the bioeconomy has become closely linked with the circular economy concept.*
- *Bioeconomy policy papers in Anglo-Saxon countries (like the UK, the USA and also New Zealand) but also in China relate more strongly to concepts of high-tech innovation, such as synthetic biology, digitisation and advanced manufacturing.*
- *In this regard, the term "industrialisation of biology" has been coined, for example, in the United States.*
- *The UK has issued a "synthetic biology strategy"*
- *In Germany terms like the "biologisation of the economy" or the "biological transformation of industry" are emerging in policy papers.*[33]

In numerous countries around the world, governments have recognised the importance of the potential of renewable bioresources, which is reflected in the inclusion of the bioeconomy in national policies (see Figure 3.6) and related initiatives.

A positive phenomenon is the openness to development based on the bioeconomy not only in societies in the Northern Hemisphere, but also in countries

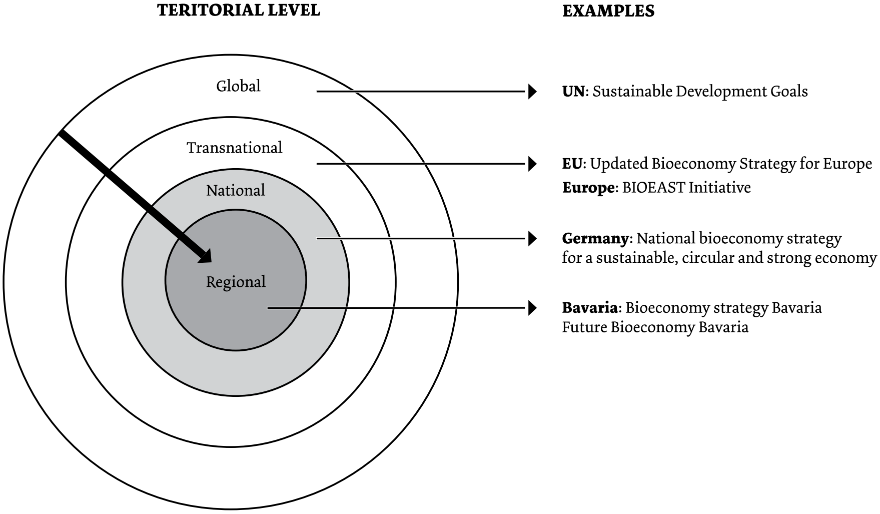

Figure 3.5 Example of territorial dimension of bioeconomy strategic support.

Source: Own elaboration.

with low and medium levels of development,[34] as the authors show, for example, in East Africa, which is supported by the Bio-Innovate Network for East African Development (Bio-Innovate Africa). The programme focuses on supporting bio-innovation policies that enable technology transfer and business development in Burundi, Ethiopia, Kenya, Rwanda, Tanzania and Uganda. The authors also report that, in Latin America and the Caribbean, the United Nations Economic Commission for Latin America and the Caribbean (UN ECLAC) organises macro-regional events on the bioeconomy to promote the exchange of information on policies and successful private sector and research initiatives. In this way, ECLAC seeks to coordinate various existing campaigns and initiatives and to further develop common policies and programmes in the field of the bioeconomy.[35]

However, it is necessary to properly manage the bioeconomy so that the countries of the Global South avoid the ‘Resource Curse’, instead using resources for their own development and needs. The European vision of the bioeconomy is based on the idea of a low-emission, resource-efficient economy and a strengthening of the labour market, especially in vulnerable rural areas. Bioeconomy policy most strongly addresses food security, as well as biomass use and its processing, thanks to innovative technologies. It promotes sustainable production and consumption and is supported by a strong policy framework, research and development infrastructure and cooperation networks. The situation is similar in the USA, where even stronger emphasis is placed on biotechnology and innovation. In the case of the Global South, while the awareness and presence of the bioeconomy is a positive phenomenon, specific constraints related to the lack of access to financial resources and

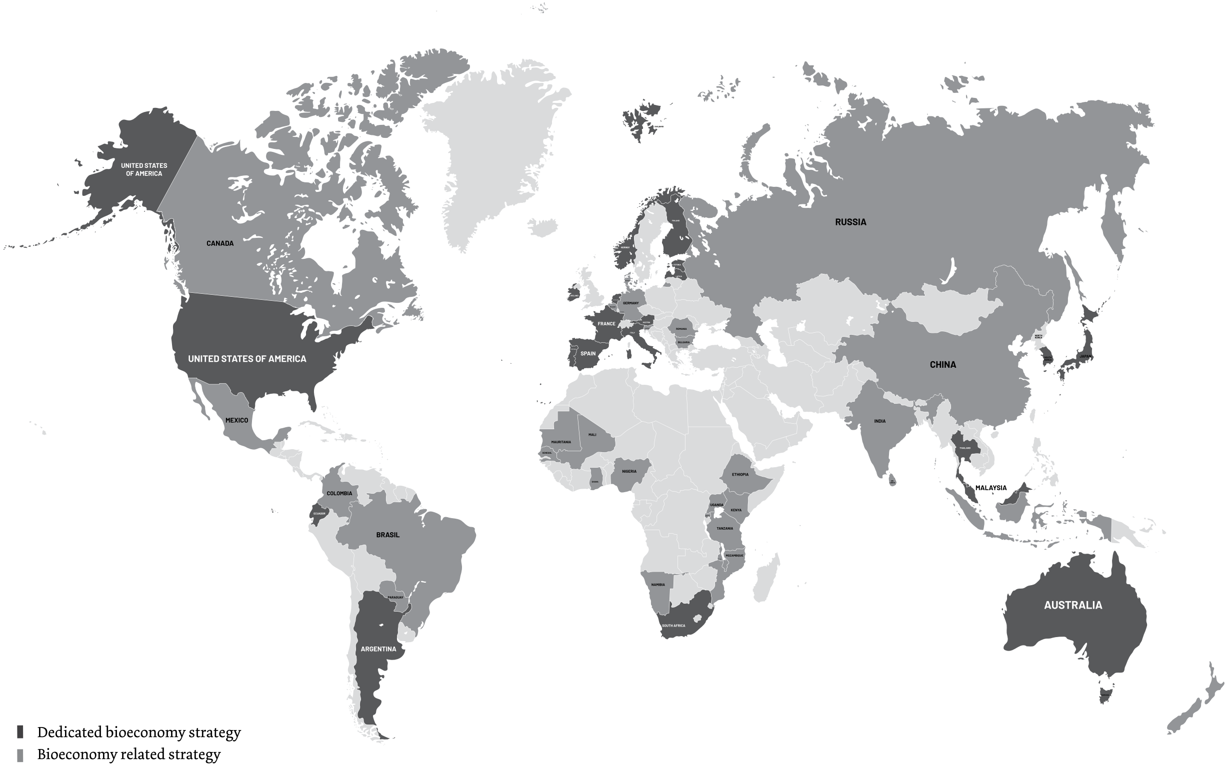

Figure 3.6 Bioeconomy and bioeconomy-related strategies.

Source: Own elaboration based on: Teitelbaum L., Boldt Ch., Patermann Ch., 2020. International Advisory Council on Global Bioeconomy (IACGB), Global Bioeconomy Policy Report (IV): A decade of bioeconomy policy development around the world and EC, 2022a, Bioeconomy Strategy. Knowledge for Policy, Knowledge Center for Bioeconomy, https://knowledge4policy.ec.europa.eu/bioeconomy/bioeconomy-strategy_en research funding, as well as the lack of a broadly understood infrastructure and the low level of innovation in many countries of the Global South, must be taken into account when implementing measures. Other problems relate to the institutional environment, including its instability and the possible lack of readiness of local markets for bio-based products. Finally, the ecological environment, access to bioresources (which is limited both by ongoing climate change and by the unequal distribution of resources due to social and political conditions) and their sustainable utilisation might may prove to be obstacles that will prevent the realisation of the potential of the bioeconomy in some countries.

One country that has avoided these pitfalls is Costa Rica, a biohub country that is home to 6 per cent of the world's wildlife, although it accounts for only 0.03 per cent of the world's surface area. Costa Rica's strategy is based on innovation and tradition and relates to 5 areas[36,37]:

- Rural development,
- Biodiversity,
- Biorefineries,
- Biotechnology, and the
- Urban bioeconomy.

In addition to the traditionally included decarbonisation strategies and the replacement of fossil resources with renewable ones, one of the goals directly mentioned in Costa Rica's strategy is the protection of biodiversity and natural resources. The idea is to create economic initiatives whose primary goal is environmental protection, with profits coming second. In order to promote 'green businesses', a financing platform for bio-business has been created through which you can obtain support and funding. In addition to environmental priorities, there are also social priorities, including equity (for example 45% of the initiatives are led by women).

3.3.1 Bioeconomy policy in the EU

In 2012, the European Commission presented its first bioeconomy strategy, in which the bioeconomy was understood as the utilisation of renewable resources and their conversion into food, animal feed, bioproducts and bioenergy. It assigned a special role to agriculture, forestry, fisheries, food and paper production, chemicals and energy and emphasised the innovative nature of the bioeconomy sectors (life sciences, earth sciences, ecology, food sciences, social sciences), technologies (biotechnology, nanotechnology, ICT), engineering and traditional local knowledge. The strategy was focused on efficient use of renewable resources and the aspect of research and innovation. However, it has become apparent that this understanding of the bioeconomy can lead to its negative environmental and socio-economic impacts. One important change introduced in the updated strategy in 2018 was an element of planetary limitation, substitution of harmful products and regional development. The main objectives of the bioeconomy strategy were defined as follows:[38]

- Ensuring food and nutrition security,
- Ensuring the sustainability of natural resources,
- Reducing dependence on non-renewable, non-sustainable resources – both domestic and international,
- Mitigating and adapting to climate change, and
- Strengthening European competitiveness while creating employment opportunities.

The European Union is often cited as a leader in supporting the bioeconomy. As noted by Czyżewski et al.,[39] the political decisions taken by the EU to implement the bioeconomy strategy, together with the implementation of the global development goals, the Europe 2020 economic strategy, the forestry strategy, the circular economy and the blue economy, give a strong impetus to the implementation of the bioeconomy in the member states, as well as at regional and local level. However, EU countries have responded differently to this impetus. According to Ronzon et al.,[40] Northern EU member states are transitioning to the bioeconomy by modernising their bioeconomy activities and implementing structural changes. Other Northern and Western EU member states are still in the early stages of the transition, while in the countries of Central and Eastern Europe (CEE) such a transition is still in sight. Therefore, according to Töller et al.,[41] bioeconomy policy in Europe "can by no means be characterised as a settled policy area, but at most as a somewhat scattered and loose constellation of variously settled sub-policy areas in the field of biomass production, processing and use". A synthesis report for the European Commission's Bioeconomy Knowledge Centre for 2020 suggests that uncoordinated and reactive policies may be the most realistic future for the bioeconomy.

The latest progress report on the EU bioeconomy strategy,[42] which was published on the tenth anniversary of the implementation of the first bioeconomy strategy, again shows some positive trends, however, highlighting that national and regional bioeconomy strategies are growing in number across Europe (see Figures 3.7 and 3.8). All European strategies at national and regional levels in the area of the bioeconomy see it as a way to achieve economic growth, create jobs and boost innovation. In most of the cases, social and environmental issues are addressed, including climate and the protection and restoration of ecosystems, as well as issues of food safety and security, and health. One of the key goals of the transformation to the bioeconomy is to move away from economies based on fossil fuels towards those based on renewable biological resources; although specific priorities vary depending on the needs, resources and perceived problems of countries.

The bioeconomy is supported by various EU instruments, such as the Common Agricultural Policy (CAP), the European Regional Development Fund (ERDF), the European Maritime and Fisheries Fund (EMFF), LIFE, the Innovation Fund and the Horizon 2020 and Horizon Europe programmes

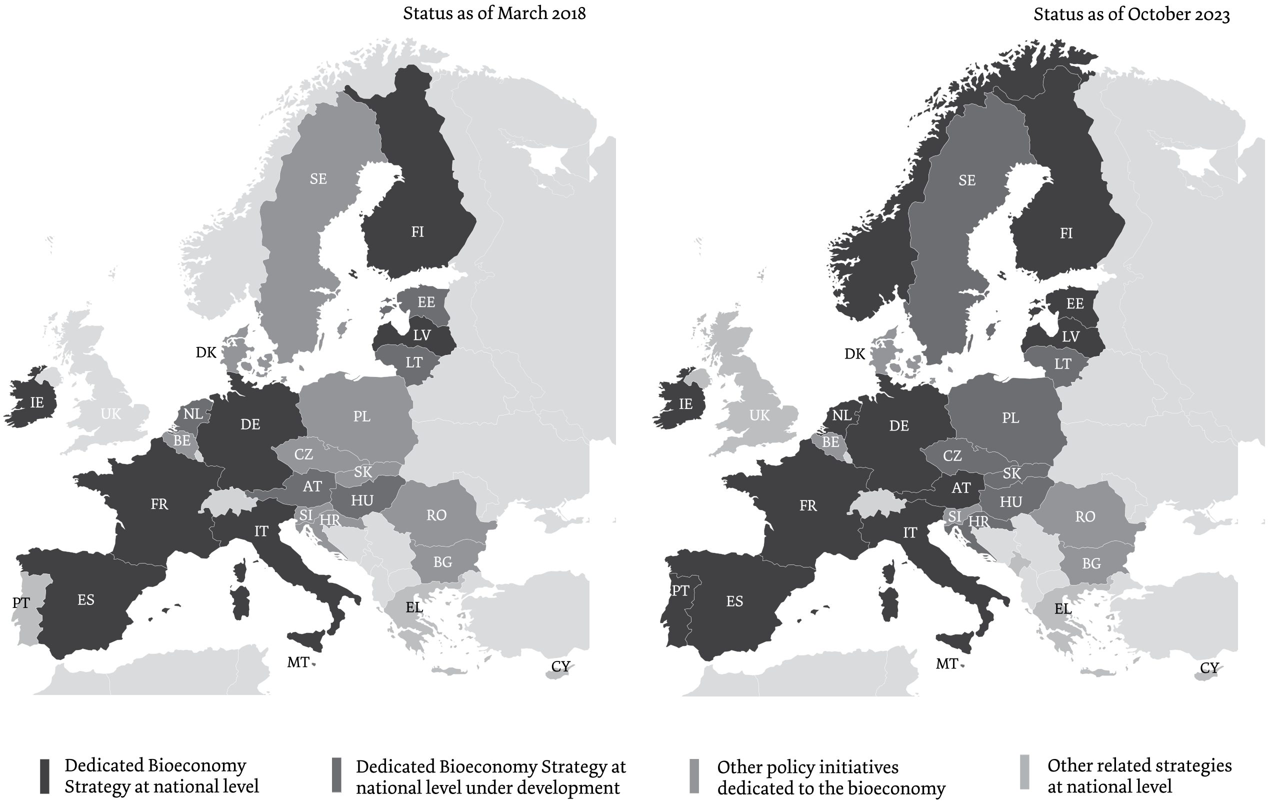

Figure 3.7 Development of national bioeconomy strategies in the EU since the adoption of the EU bioeconomy strategies[43].

Source: Own elaboration based on Bioeconomy Strategy. Knowledge for Policy, Knowledge Center for Bioeconomy.

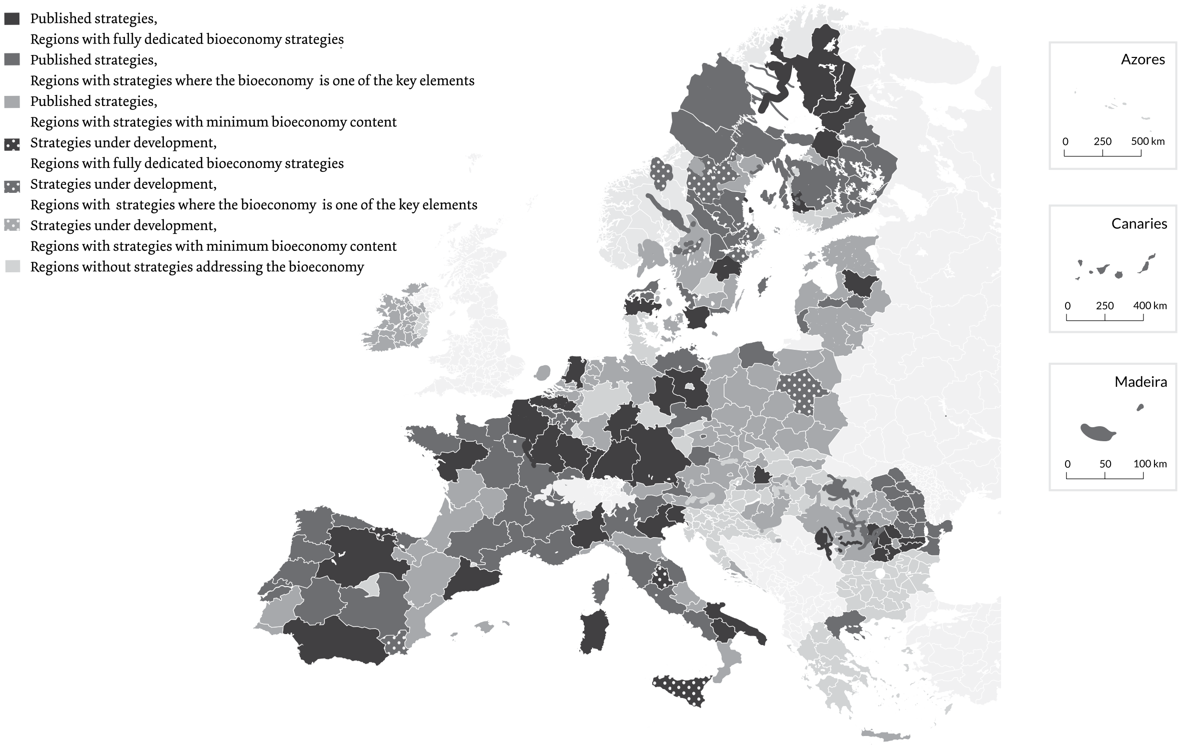

Figure 3.8 EU regions with bioeconomy strategies.

Source: Own elaboration based on Haarich and Kirchmayr-Novak, 2022.

with their partnerships and missions (e.g. land and marine missions). It should be noted that the European Territorial Cooperation Programmes – Interreg – also play an important role in the development of regional and especially multi-regional strategies in the field of the bioeconomy.[44] Interreg projects are often cited as a source of regional strategic frameworks or action plans in countries without a systematic introduction of the bioeconomy at the regional level. As Mubareka et al.[45] show, three large macro-regional bioeconomy initiatives involving governmental authorities can currently be seen in Europe:

- BIOEAST – Central-Eastern European Initiative for Knowledge-based Agriculture, Aquaculture and Forestry in the Bioeconomy *(described in the text below)*;
- Nordic bioeconomy *(under the Nordic Bioeconomy Panel, it draws up proposals for a strategy covering the area and outlines options and practical measures to promote sustainable bioeconomies)*;
- Bioeconomy in the Baltic Sea Region *(Nordic Council of Ministers provides an access point and support function for stakeholders that wish to pursue bioeconomy cooperation activities that support overall objectives of the EU Strategy for the Baltic Sea Region)*.

Mubareka et al.[46] also highlight four additional macro-regional initiatives supported by Interreg, namely:

- AlpLinkBioEco, Linking BioBased Industry Value Chains Across the Alpine Region: *a cross-regional and circular bio-based economic strategy which released the Masterplan towards a joint bioeconomy strategy for the Alpine Space*.
- BIO-ECOnomy Research Driven Innovation for the Adriatic–Ionian Region (Bioeco-RDI-ADRION): *an initiative to support the development of a regional innovation system for the Adriatic–Ionian area*.
- Bio-Innovation Support for Entrepreneurs throughout NWE regions (BioBase4SME): *an initiative involving organisations from 6 European countries (BE, DE, NL, IE, FR and the UK) to advise SMEs from across Northwest Europe on how to develop new ideas into marketable products*.
- Danube Region (DanubeBioValNet): *a cross-regional partnership involving 16 partners from 10 Danube regions to develop three bio-based value chains*.

Strategic support is no longer limited to the territory of individual states, but is increasingly appearing at the regional level. Haarich and Kirchmayr-Novak[47] show that 194 regions in the EU-27 (at NUTS 1, NUTS 2 or NUTS 3 level) have, or are working on, a strategic framework related to the bioeconomy (Figure 3.7). The authors identified a total of 359 bioeconomy-related strategies at regional level in the EU-27 in 2021. The strength of the focus of the bioeconomy strategies varied, so the authors classified the strategies into the following four types:[48]

- Full/dedicated bioeconomy strategies: those strategies that are exclusively focused on bioeconomy deployment, be it in one sector, many sectors, one part of the value chain or different parts of the value chain. Usually, these strategies or plans have bioeconomy in the title and a large share of the content is on the deployment of the bioeconomy
- Strategies with a strong bioeconomy focus: those that also focus on other topics, themes or sectors, but where the bioeconomy is at least a key element, e.g. at least one chapter, one priority axis, one objective of a wider strategic framework focuses on the bioeconomy and describes its deployment in detail
- Embedded strategy: when the main theme and a large share of the content is on a wider topic or pursues a wider objective – e.g. economic development, sustainable development, blue growth – but where the bioeconomy is also mentioned or is part of the content/objectives/actions
- Sectoral strategy: when the title of the document and a large share of its content are specifically dedicated to the development of a sector, e.g. agriculture, agri-food, forestry, waste plans, energy plans, including or mentioning bioeconomy-related topics/actions/objectives. We have not included sectoral strategies per se when they do not show any content or linkage to bioeconomy-related concepts, actions or objectives.

In relative terms, i.e. in relation to the total number of regions in each country, all regions in Belgium, France, Italy and the Netherlands have bioeconomy frameworks. Table 3.2, presenting selected EU countries, shows that only Lithuania and Latvia do not have at least half of the regions with a bioeconomy strategy. Due to significant differences in the availability and abundance of information for different countries, the EU member states are grouped into three clusters presented in respective sections:[49]

- countries with no bioeconomy-relevant regional strategies: Bulgaria, Cyprus, Estonia, Luxemburg, Malta, Slovenia,
- countries with regional strategic action to deploy the bioeconomy (between 1 and 15 regions with bioeconomy-relevant strategic frameworks): Austria, Belgium, Czech Republic, Germany, Denmark, Greece, Croatia, Hungary, Ireland, Lithuania, Latvia, the Netherlands, Portugal, Romania, Slovakia,
- countries with intense regional strategic action to deploy bioeconomy (more than 15 regions with bioeconomy-relevant strategies and usually more than one strategy per region): Spain, Finland, France, Italy, Poland, Sweden.

Fund et al.[50] identified 83 regional strategies that relate to the bioeconomy as a sectoral strategy (e.g. forestry or waste strategies) and another 209 that recognise the bioeconomy as a topic embedded in a broader strategic framework (e.g. circular economy). The interdependence and coherence between the supranational (i.e. EU), national and regional levels is demonstrated by Haarich and Kirchmayr-Novak,[51] as the regional strategic frameworks of the

Table 3.2 Overview of regional bioeconomy strategies in the selected states of EU in 2021

State	*National-level bioeconomy strategy*	*Regions with a dedicated bioeconomy strategy*	*Regions with strategies where the bioeconomy is one of the key elements*	*Regions with strategies with minimum bioeconomy content*	*Total number of regions with strategy*	*Total number of regions in the country*
Austria	X		1	7	8	9
Czech Republic			2	9	11	14
Germany	X	6	2	5	12	16
Denmark		1	1	2	4	5
Hungary				10	10	20
Lithuania			1		1	10
Latvia	X	1	1		2	6
Slovakia		1		4	5	8
Finland	X	3	10	3	16	19
Italy	X	6	7	6	19	21
Poland			1	14	15	17
Sweden	X	2	8	6	16	21

Source: Own elaboration based on: Haarich and Kirchmayr-Novak, 2022.

EU regions are directly related to the five objectives of the EU bioeconomy strategy. The most frequently mentioned objective is "sustainable management of natural resources". "Reducing dependency on non-renewable resources" and "Strengthening regional competitiveness and creating jobs" are also important objectives addressed by regional strategies. The authors also show in the study that certain patterns can be observed in individual countries, e.g. how and within which broader frameworks the bioeconomy is integrated. In Spain, for example, the bioeconomy is often included in circular economy strategies, while, in Italy, it is usually addressed in sustainable development strategies. In Finland, the bioeconomy is included in almost all regional development plans and in many smart specialisation strategies, but often also in climate plans.

The mere creation of strategies for the development of the bioeconomy in the region does not mean that the identified activities will be implemented. Kardung et al.[52] show that, although many European regions have expressed ambitions to valorise agricultural, forest, marine or urban biomass and waste into new bioproducts (i.e. 100–170 regions have a bioeconomy-related focus in their RIS3, depending on the selection criteria), only a few regions have successfully completed the development path and managed to establish a bioindustry (e.g. the Hauts-de-France and Grand Est regions as part of the IAR cluster in France, Central Finland, the Biobased Delta in the Netherlands).

3.3.2 Bioeconomy policy in Central Europe

Central European states and regions are relatively behind on implementation, although they are close to Germany, which is one of the leaders in political support for the bioeconomy in the EU, and, in a way, German activities preceded the support and strategic anchoring at the EU level.[53,54] Nevertheless, the findings of the European Commission from 2022 show that progress has been made in the implementation of the bioeconomy in the countries of Central and Eastern Europe, to which significant financial contributions from the EU and the creation of new forums and networks have contributed. Most of these countries have started working on a national strategy for the development of the bioeconomy (Figure 3.6). Based on the value of the aggregated indicator of the level of bioeconomy development, according to Czyżewski et al.,[55] Poland belongs to the group of countries with high resources in agriculture and aquaculture, and partly in forestry and with a significantly higher efficiency of the bioeconomy (e.g. similar to Finland or France), while the second group of countries with a significantly lower efficiency of the bioeconomy than in highly developed countries consists of Hungary, the Czech Republic and Slovakia. Also, according to Haarich and Kirchmayr-Novak,[56] Poland is ranked among the countries with intense regional strategic action to deploy the bioeconomy.

The different levels of preparation of the countries for the implementation of the bioeconomy are also visible from the point of view of the sectors represented in the strategy (Table 3.3). According to the Bioeconomy Country Dashboard (European Commission, 2023c), from the Central European states, Austria and Germany have very comprehensive and broad strategies, while, in the case of the Czech Republic and Poland, some sectors are missing (bio-based textiles, fisheries, organic waste, wood, wood products and furniture). In contrast, other countries (Croatia, Estonia and Lithuania) participating in the BIOEAST initiative (for which data are reported) have included all monitored sectors in their strategies.

A major contribution to the development and political anchorage of the bioeconomy in Central and Eastern Europe can be linked to the BIOEAST initiative, which supports the development of the bioeconomy in 11 Central and Eastern European countries. The BIOEAST initiative is supported by the European Union's Horizon 2020 research and innovation programme. This Central Eastern European initiative for knowledge-based agriculture, aquaculture and forestry in the bioeconomy promotes a strategic vision for the development of the bioeconomy in Central and Eastern Europe, including countries such as the Czech Republic, Hungary, Poland, Slovakia and Estonia, as well as in Southeastern European countries such as Bulgaria, Romania, Slovenia and Croatia. The forerunners of this initiative can be seen in the Forum of Bioregions of Central and Eastern Europe or the DanuBioValNet project. The BIOEAST Initiative has played a pivotal role in shaping bioeconomy research and innovation agendas, fostering international collaboration, and advocating

Table 3.3 Sectors included in bioeconomy strategies in Austria, Germany and BIOEST countries

State		*Agriculture*	*Aquaculture*	*Bio-based chemicals and materials*	*Bio-based textiles*	*Bioenergy (including transport biofuels, bioelectricity and H&C)*	*Biotechnology*	*Ecosystem services*	*Fisheries*	*Food*	*Forestry*	*Organic waste*	*Pulp & paper*	*Wood, wood products & furniture*	*Other*
Germany		V	V	V	V	V	V	V	V	V	V	V	V	V	V
Austria		V	V	V	V	V	V	V	X	V	V	V	V	V	V
B	**Croatia**	V	V	V	V	V	V	V	V	V	V	V	V	V	V
I	**Czech Republic**	V	V	X	X	X	V	V	X	V	V	X	X	X	V
O	**Estonia**	V	V	V	V	V	V	V	V	V	V	V	V	V	V
E	**Lithuania**	V	V	V	V	V	V	V	V	V	V	V	V	V	V
A S	**Poland**	V	X	V	X	V	X	X	X	V	V	X	X	X	X
T	Bulgaria, Hungary, Latvia, Romania, Slovakia, Slovenia – sectors are not reported														

Source: European Commission, Bioeconomy country dashboard (online).

for the effective utilisation of research potential in the Central and Eastern European region. The initiative has been actively promoting collaboration and contributing to the field of bioeconomy by strategic conferences (for example, setting the agenda for bioeconomy research and innovation within the framework of Horizon 2020 and Horizon Europe), consultation and advocacy (actively engaged in the consultation process for the long-term EU strategy in agriculture research and innovation, advocating for more effective use of research potential within Horizon 2020), policy guidelines and declarations (has provided policy guidelines through workshops and signed crucial declarations like the Lodz Declaration, emphasising commitment and priorities for participating countries), international collaboration (has fostered collaboration with neighbouring countries through workshops, conferences, and initiatives, promoting the exchange of ideas and joint efforts in the bioeconomy sector) and position papers (position papers on bioeconomy and green investments, reaffirming commitment and outlining strategies for knowledge-based solutions in Central and Eastern Europe). Based on these activities, the BIOEAST Initiative continuously helps to:[57]

- Trigger strategic thinking at the governmental level and transnational peer-to-peer development of national circular bioeconomy strategies in BIOEAST countries.
- Emphasise and encourage the role of multi-stakeholder and multi-actor approaches as well as the co-creation of innovation in developing new value chains to advance bioeconomies to enhance the engagement of stakeholders from academia, business and also the non-profit sector in the bioeconomy.
- Develop a bottom-up stakeholder-driven approach for a consolidated bioeconomy Strategic Research and Innovation Agenda (SRIA) for the BIOEAST countries.
- Increase the visibility of the bioeconomy in the BIOEAST region.

Nevertheless, it can be argued that due to the lack of clearly defined strategies (see the Bioeconomy Country Dashboard on the European Commission's website),[58] the bioeconomy is being applied to varying degrees in the countries of Central and Eastern Europe. For example, in July 2019, the Ministry of Agriculture of the Czech Republic presented the Bioeconomy Concept for the period 2019–2024, in which it identifies the bioeconomy as one of its main priorities. Bioeconomy activities in CEE are mainly concentrated in the agriculture, food and forestry sectors, with some manifestations in the energy sector.[59,60] Despite this gradual development, the potential of the CEE countries remains untapped, especially in terms of modernisation and increasing labour productivity along the lines of the Western and Northern EU countries.[61]

Systematic policy attention to the bioeconomy gained momentum after 2010, when it was aligned with discussions on sustainable development, renewables and climate change. Bioeconomy policies, which are framed by strategies, regulations, initiatives and action plans, aim to promote the sustainable use of biological resources in different sectors. Specifically, the main objectives include increasing the production of bio-based products and bioenergy, ensuring food and energy security, developing sustainable supply chains, improving natural resource management and mitigating the impacts of climate change. Therefore, the bioeconomy has the potential to become a key element of sustainable development and the reduction of negative environmental impacts. It is essential that bioeconomy policy is firmly anchored in environmental policy, respects the economic and social needs of the territory and is supported at national and international levels. Aligned with ambitious EU goals for sustainability, food security, and reduced reliance on natural resources and fossil fuels, the bioeconomy has emerged as a crucial element within the European Green Deal. The bioeconomy is intricately linked with various European strategies such as agriculture, energy, and the circular economy. It aligns with 15 Green Deal initiatives, including adaptation, biodiversity, the circular economy, and renewable energy.

Policy actions to promote the bioeconomy and establish new bio-based industries can be implemented at various levels, including regional, national, transnational, or global levels. While there is no global strategy for the bioeconomy, the Sustainable Development Goals provide a logical foundation for strategic documents. Effective bioeconomy management is crucial for countries in the Global South to avoid potential challenges, including the "Resource Curse". The European and US visions of the bioeconomy emphasise low emissions, resource efficiency, and innovation, while the Global South faces specific constraints like limited access to financial resources, infrastructure challenges, and low levels of innovation. Transnational initiatives, such as the EU's bioeconomy strategy, and cross-border initiatives, like BIOEAST, lay the groundwork for national and regional bioeconomy development strategies. Governments worldwide have recognised the potential of renewable bioresources, leading to the inclusion of the bioeconomy in national policies and initiatives. The European Commission's bioeconomy strategy, initially presented in 2012, emphasised the utilisation of renewable resources for food, animal feed, bioproducts, and bioenergy, with a focus on agriculture, forestry, fisheries, and related sectors. However, concerns arose regarding potential negative environmental and socio-economic impacts. In 2018, an updated strategy incorporated planetary limitations, substitution of harmful products, and regional development, with objectives centred around food security, the sustainability of natural resources, climate change mitigation, and European competitiveness. While the European Union is regarded as a bioeconomy leader, member states' responses vary. Northern EU states are advanced in their bioeconomy transition, while others are in the early stages, and Central and Eastern European countries are still catching up. Central and Eastern European countries, although behind on implementation, have made progress, notably through the BIOEAST initiative, which supports 11 countries in developing the bioeconomy. However, the degree of bioeconomy application varies in CEE countries, and their untapped potential, especially in terms of modernisation, remains a focus for future development.

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4 Selected management problems in the world of the circular bioeconomy

Veronika Svatošová, Gabriela Chmelíková, Barbara Kiełbasa, Dżamila Bieńkowska, Jiří Nesiba and Sylvie Formánková

4.1 Introduction

At the outset, it is necessary to introduce the relationship between the philosophical concept of sustainable development traditionally referred to as Corporate Social Responsibility (CSR) and contemporary approaches which emphasise the importance of implementation of management tools, including the concept of circular bioeconomy. CSR in its most popular form is presented based on the concept of the triple bottom line (TBL), an idea representing a utopian vision of harmony among three areas, i.e. economics, environmental protection and a social approach. CSR has almost a century of development behind it, particularly in the context of business ethics. The circular bioeconomy builds on the triple bottom line in general terms but deals with specific methodological steps for applying the concept of CSR.[1]

CSR has been defined as the voluntary integration by businesses of social and environmental issues into their activities and interactions with stakeholders. The first concepts of CSR already sought to promote a balance in the development of civil society (known as the Berle–Dodd debate) in the context of New Deal policies in the USA. The search for concepts of balance in management decision-making continued mainly in the developed Western countries from the 1950s onwards, in line with the development of the environmental movement, demands for social liberalism and on the basis of new scientific evidence of the environmental impact of economic production activities (e.g. the controversy over the use of leaded petrol, nuclear energy or the agricultural use of DDT). The concept of CSR offered an ideal solution in order not only to maintain economic growth, but also to ensure a more humanistic and responsible approach to management.

A growing number of proponents are advocating the effective incorporation of sustainability issues and CSR objectives into the framework of day-to-day management decision-making. Historically, since the earliest CSR models (e.g. Carroll's pyramids), the problem has been that there is no one "right" way for companies to practice CSR. There have also been discussions as to whether the concept of accountability is itself vague (the Friedman doctrine).

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Since the 1970s, CSR concepts have been criticised for serving to improve the reputation of organisations in the eyes of the public as a form of *ethics washing*, mainly used by global corporations to influence public opinion (greenwashing, whitewashing, bluewashing, etc.) as a form of marketing.[2] Therefore, CSR has gradually evolved since the 1980s into a more applied form of management and defined a new theory of stakeholders and triple bottom line theory. The process of development of CSR was framed by discussions mainly between economists, politicians and environmental non-profit organisations that were concerned with environmental protection.

The integration of multiple approaches revealed previously unexplored hidden consequences of economic action that may manifest themselves over time or geographically at a different location from where economic activity originates. The different approaches eventually settled on the three pillars, which are generally referred to as *people*, *planet* and *profit*. According to the original concepts, these three pillars are meant to balance each other in the management decision-making of multinational corporations, as well as in the decision-making of national governments, as any corporate CSR initiatives strive to positively contribute to the public, the economy or the environment.[3] The three pillars concept has been termed the *triple bottom line* (TBL or 3BL), following the model from accounting. For business accounting, the *bottom line* means a relation between profit or loss, which is usually recorded at the very bottom line on a statement of revenue and expenses (known as a cost–benefit analysis). The triple bottom line adds two more *bottom lines*: social and environmental (ecological) concerns.

Original proposals concerning the balancing of key areas of modern civilisation included both dualistic concepts (the so-called double bottom line, DBL or 2BL) and, in contrast to them, multi-integral concepts (the so-called integrated bottom line). The three pillar model (TBL) has gradually gained ground. John Elkington, an American ecologist, who first used the term "triple bottom line" in his 1994 article,[4] is considered to be its founder. This model, which calls for harmony among the three basic pillars, soon became a symbol for the whole concept of CSR. In TBL, three circles are similarly intertwined (the "Venn diagram"). Sustainable growth was thus depicted in this concept as a harmonious blending of the interests of economics (profit), ecology (planet) and society (people).

This three-domain approach has gradually become the accepted symbol of CSR management as a whole.[5] According to anthropological and religious studies, it is not even possible that other models than the threefold model could gain such popularity, because it is the archetypal trifunctional model through which the oldest societies already expressed stability and sustainability (the trifunctional hypothesis, cf. Dumézil[6]). The question remains whether these three pillars – people, planet and profit – are chosen with sustainability in mind or whether they are 'just' a simple popularisation of the quest for sustainability. So far, the theoretical requirement for the necessity of the interlacing of the three pillars (people, planet, profit) and their mutual indeterminate harmony seems more like a general philosophical model than a practical management tool.[7] In the late 20th century, this theory certainly played a significant role in popularising the topic of sustainable development. In the 21st century, this philosophical concept is being replaced by approaches that offer applied methods such as the circular bioeconomy. The traditional concept of CSR and its triple bottom line as theoretical models without a clearer possibility of implementation in concrete organisations is proving to be an inadequate tool for contemporary management.[8]

Compared to the CSR concept and the triple bottom line, the circular bioeconomy is a specific tool that can be used in measures that have the ability to describe the environmental impact of an organisation (e.g. in Life Cycle Assessment concepts). Therefore, the circular bioeconomy can be considered to be a practical extension of the original CSR theories.[9] The circular bioeconomy model requires the deepest principles of CSR to be put into practice. CSR and the circular bioeconomy fall under same umbrella concept of *sustainability*,[10] though the two models do not overlap, because it cannot be affirmed that circular bioeconomy practice is necessarily the environmentally desirable option.[11]

The two concepts still have an important mutual function in defining sustainability. CSR is a theoretical framework for sustainability and the circular bioeconomy is one of the applications of CSR. The two approaches must therefore be understood in an interconnected way. Here, there is a proposition to show how the triple bottom line approaches to the issue of CSR and the circular bioeconomy can be combined into a single functional model that integrates both the theoretical and practical aspects of sustainable development. Among the many approaches, one cannot fail to mention the theory of the social trinity, developed in the early 20th century by the philosopher Rudolf Steiner, who first defined the relationship between what would later come to be known as CSR and the circular bioeconomy.

The idea of tripartism leads to the elimination of the reductionist approach and, at the same time, to the overall development of society. According to Steiner, it is necessary to have the three links in balance, but at the same time independent of each other, so that they create the conditions of freedom. Thus, in a social organism, it is necessary to have economic freedom, cultural freedom and legal freedom in balance. In the field of economics, Steiner describes economic relations as deriving from natural conditions. Thus, he anticipated the model of the circular bioeconomy a century in advance (Figure 4.1).

The principles of the economic pillar (profit), the environmental pillar (planet) and the social pillar (people) are uncritically perceived as traditionally unchangeable in the current CSR concept. However, the identification of the focus of the three pillars does not include a specific methodology on which pillars are based. Current economic approaches have many different and often-divergent interpretations. In the same way, there are also many conceptions of environmental and ecological conservation, e.g. the distinction between shallow and deep ecology which was already pointed out by a number of scholars

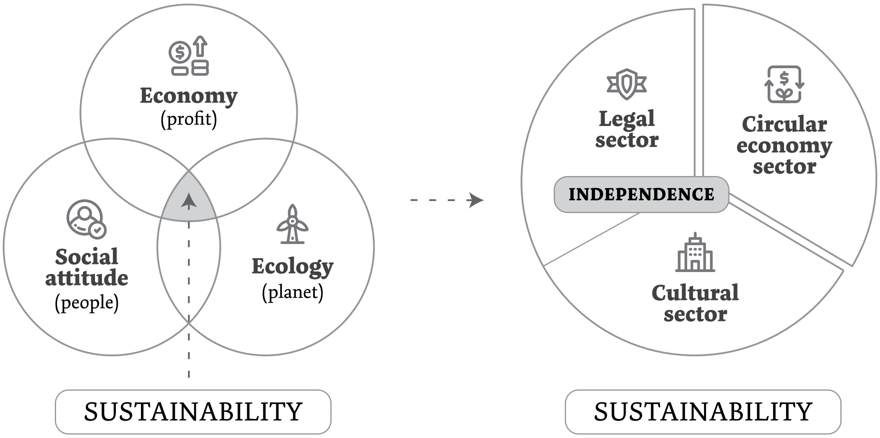


Figure 4.1 Relationship of the traditional triple bottom line (left) to the new design (right).

Source: Own elaboration based on Findeli, A.[12]

at the time when CSR was popular, amongst other things, drawing on Steiner's ideas as part of a philosophy referred to as an *ecosophy*.[13] The current trends of subordinating economic decision-making to environmental conditions and linking them together in a relation of circularity reflect this philosophical idea of Steiner.

According to Steiner, each pillar creates the possibility of freedom for man only by its independence from the other pillars. The definitions of each pillar must therefore be revised. The three elements should be defined according to the cultural-spiritual pillar (the conditions for a free environment of creation, creativity and innovation), the pillar that provides for legality (the field of education and finance) and the circular-economic pillar (i.e. the area linking ecology and economics). In this way, according to Steiner, a sustainable, stable and yet free environment can be created. Therefore, according to this new conception, it is essential that the economic and environmental aspects be linked together into a common pillar. Separating them into two different pillars creates instability and unsustainability.[14]

4.2 Values as the source of the circular bioeconomy strategy and business model – the stakeholder vs the shareholder approach

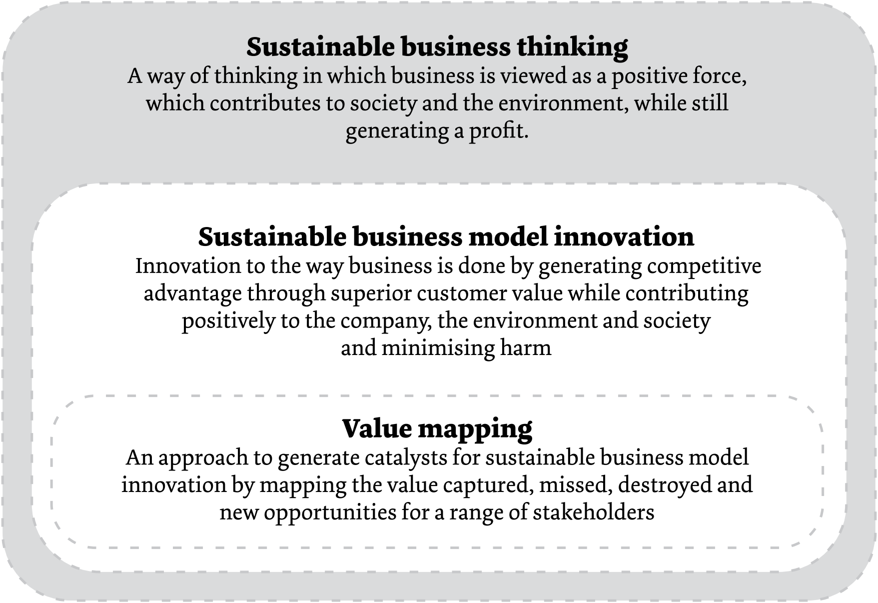
Values play a crucial role in shaping a company's strategy, particularly when formulating a circular bioeconomy strategy. Serving as an ethical compass, values guide decision-making processes and define the character of the organisation in the context of sustainable and responsible practices. When aligned with strategic objectives, values establish a cohesive framework that not only prioritises profitability but also emphasises sustainability and ethical responsibility.

In the circular bioeconomy, where resource efficiency and environmental impact are central considerations, integrating values into the strategy becomes even more critical.

The distinction between stakeholder and shareholder approaches becomes pivotal in this context. A shareholder approach, which prioritises financial success for owners,[15] may fall short when it comes to addressing the complexities of a circular bioeconomy. Conversely, a stakeholder approach considers the interests of employees, customers, communities and the environment, recognising the interconnectedness of these factors. However, the question arises as to what extent the theory of business recognises the influence of all stakeholder groups on the value creation process. Friedman and Miles[16] claim that the primary purpose of a firm is to maximise shareholder wealth. They argue that managers have a duty to act solely in the best interest of shareholders and that any actions taken for other stakeholders must ultimately serve the goal of increasing shareholder value. In contrast, Freeman (2004) and De Gooyert et al. (2017) argue that the purpose of a firm is to create value for all stakeholders, including employees, customers, suppliers, communities and shareholders. Freeman believes that firms should not prioritise the interests of shareholders above all else and should consider the broader impact of their actions on society.

According to Friedman and Miles, managers should focus solely on the maximisation of profit within the existing legal framework. Ferrero et al.[17] argue that Friedman and Miles' arguments are premised on the assumption of an economy where businesses benefit from limited liability protections. This enables corporations to reap profits privately while shifting the burden of losses onto external parties. In order to maintain coherence with their economic principles, Friedman and Miles face the choice of either relinquishing the concept of limited liability or adjusting their stance on Corporate Social Responsibility and their shareholder-centric model of business. This statement is in accordance with the findings of Schaltegger et al.,[18] who claim that the objective of sustainable business modelling is to identify solutions that allow firms to capture economic value, whilst generating environmental and social value, thereby establishing the business case for sustainability. Bocken et al.[19] state that sustainable business models must, as a prerequisite, be economically sustainable, and, that, at the same time, a holistic view of the value proposition is required that includes benefits and costs to other stakeholders. The process of adopting a sustainable business model requires significant changes in the thinking of business decision-makers. Bocken et al.[20] claim that this process requires a change in thinking about business that seeks to integrate consideration of the three – social, environmental, and economic – dimensions of sustainability. Figure 4.2 introduces the conceptual framework for integrating stakeholder concerns into the business decision-making process.

To consider all stakeholder interests equally, along with their interrelatedness, Bocken et al.[22] introduced an instrument which they called a Value Mapping Tool. With this instrument, they operationalised the last phase of the



Sustainable business thinking

A way of thinking in which business is viewed as a positive force, which contributes to society and the environment, while still generating a profit.

Sustainable business model innovation

Innovation to the way business is done by generating competitive advantage through superior customer value while contributing positively to the company, the environment and society and minimising harm

Value mapping

An approach to generate catalysts for sustainable business model innovation by mapping the value captured, missed, destroyed and new opportunities for a range of stakeholders

Figure 4.2 Conceptual framework for integrating stakeholder concerns into the business decision-making process.

Source: Own elaboration based on Bocken et al.[21]

sustainable thinking process of the conceptual framework depicted in Figure 4.2. The aim of this tool is to understand the positive and negative aspects of the business value proposition, to identify conflicting values, and to identify opportunities to improve the overall outcome for all stakeholders. The advantage of this tool is that it enables one to facilitate a systematic value assessment, to facilitate a multiple stakeholder view of value, and to optimise value in a network of all stakeholders. The Value Mapping Tool works with given range of stakeholders (Customers, Investors and Shareholders, Employees, Suppliers, Environment, Community, Government, External Agencies, Media, Academia). The second step of the value-mapping process is the identification of values that are currently captured, destroyed, or missed, and the formulation of opportunities for additional value creation. This tool is a useful instrument for establishing and eventually transforming existing strategies into circular forms based on the principles of the bioeconomy. It is one of the ways to embody the principles of circularity in the mission, vision, and strategic goals of companies.

A different way of businesses responding to circular bioeconomy concerns is proposed by Joyce and Paquin.[23] Their Triple Layered Business Model Canvas is a tool for exploring sustainability-orientated business model innovation and it includes an economic layer based on the shareholder perspective, an environmental layer based on a lifecycle perspective, and a social layer based on a stakeholder perspective.

4.3 Circular bioeconomy and the code of ethics

A code of ethics, as the written form of an organisation's voluntary commitment to respect the general principles of sustainability manifested in management as Corporate Social Responsibility (CSR), should be based on a well-defined set of values. Codes of ethics may take different forms, but their effectiveness results from concrete, practical and clear commitments. The concepts of CSR and the circular bioeconomy complement each other in the field of ethical codes.[24] The circular bioeconomy economy is a specific area of a broad concept of responsibility within CSR that strives for sustainability. Therefore, the code of ethics can play the key role as a tool for communication with all interest groups, also known as stakeholders, in their relations with a biocircularly managed organisation.[25] The institution's code of ethics is an example where ethical and philosophical theory is put into practice in the everyday life of the organisation.

A corporate culture that implements biocircular elements creates a specific environment of values that can subsequently be transparently monitored.[26] In addition, biocircular elements in the management of the organisation create a new area for promotion of the organisation, which can report on its corporate culture using ethical codes in specific areas.[27]

An organisation implementing biocircular elements visibly integrates the types of values that shape the entire CSR movement. The biocircular commitment has a specific character. Commitment defines and creates a more stable and predictable way of acting. With the help of a voluntarily accepted commitment, the real state of the organisation's values and the model to which the organisation relates can be compared, across SMEs, multinational corporations, and public institutions.[28] Codes of ethics are a key tool for setting out voluntarily disclosed commitments that help to develop CSR within the organisation and allow ethics washing[29] to be prevented. Ethical codes allow for both a clearer examination of the impact of an organisation's activities and more effective collaboration. It can therefore be said that establishing voluntary commitments in the organisation contributes to a greater degree of responsibility, both to external stakeholders and to the internal functioning of the organisation itself.[30] It is precisely in this area that there is significant scope for action on the part of organisations implementing the biocircular economy in their management and corporate culture. They can voluntarily report on their biocircular economy commitments in these documents.

4.3.1 Ethics washing or a truly responsible strategy?

Codes of ethics can just as well be as a tool for ethics washing as a form of expression of an organisation's truly responsible strategy. Their existence in an organisation does not automatically mean that there is a responsible approach and an integral concept of ethics in decision-making. But the very existence of codes already creates a form of voluntary reporting of information about corporate culture. In the area of the circular (bio)economy, in contrast to other areas of CSR, the basic principles can be concisely and clearly expressed in concepts of circularity and bioeconomy applied in ethical codes.

Examining the voluntary commitments made by an organisation is a good point of entry where the concept of values-based management can be demonstrated. The code of ethics is an internal tool of CSR in the organisation. The assistance of another official guarantor who would approve – or control – the code of ethics is not necessary. This is in contrast to external CSR tools (e.g. ethical certification, ethical labels, ethical audits), where the role of other independent bodies is necessary. It is the area of the circular (bio)economy that is currently developing most intensively from the point of view of voluntary information, and thus codes of ethics offer a wide range of possibilities for new and direct communication with stakeholders.[31]

A code of ethics may exist in an organisation in a generally misleading and merely declaratory form if the code of ethics is not linked to a specific applied obligation. Committing to vague and general principles of CSR can only lead to general commitments without more concrete implementation of clear steps (e.g. circular models). Such an element of self-regulation can be vague and thus confusing and untrustworthy for stakeholders. However, based on the well-defined principles of the circular (bio)economy, voluntary obligations can be reported clearly and concretely. The circular (bio)economy is thus, by definition, key to the interdependence between responsibility and legal liability, providing the elements of management that allow an environment of sustainability to be created[32] (Figure 4.3).

A code of ethics is still the most widely used tool for voluntary CSR commitments.[33] Therefore, it is likely that this will also be the case in the circular (bio)economy. In the long term, the code of ethics is most often used as an internal management tool, which is used for the purposes of both external promotion and internal information in relations with various circles of multi-stakeholders.[34]

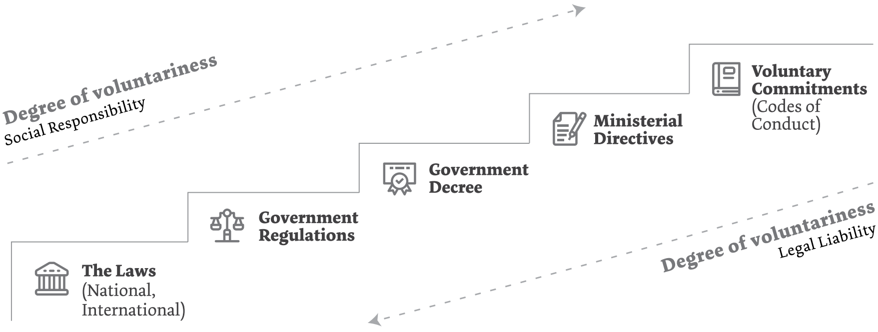


Figure 4.3 Voluntary commitments.

Source: Own elaboration.

4.3.2 Tradition and history of codes of ethics

In the field of biocircular economy, we can transfer experience from the field of CSR, which can draw on several decades of implementation in the field of corporations, SMEs and public institutions. In addition, ethical codes have a centuries-old tradition dating back to pre-modern times, when they played a fundamental role in the creation of standards in various sectors of the economy.[35] Codes of ethics were most often enforced from the beginning of the 20th century in the environment of industries that enjoyed high social prestige, e.g. in medicine, the judiciary, universities, the care professions, or the police, but the use of ethical codes has gradually spread to other sectors, including public administration, since the start of the 21st century.[36]

The essence of such a voluntary commitment is to confirm an undertaking to adhere to a certain course of action that is shared between the members of the group. Commitment means agreement with the "ideals" of such an association. An individual who becomes a member of an organisation represents the entire organisation, not just himself. Codes of ethics thus combine Corporate Social Responsibility and Personal Social Responsibility.[37] A commitment made by an individual is analogous to a commitment made by an entire organisation. This obligation arises voluntarily; therefore the member undertakes in a declaratory form to observe the ethical principles of the entire organisation. Such a declaratory commitment may take different forms. While previously such commitment were more often made orally in the form of an oath or promise, these commitments have gradually come to be statutes with a written signature.[38] Codes of ethics are thus a modern variant of voluntary commitments to respect transcendental values made in the past.[39]

The code of ethics may contain, in written form, these parts in which there is room to identify with the declared values. From the point of view of ethics and the company, the code of ethics should present the following values:

- enforcement;
- clarity;
- good role modelling;
- commitments;
- feasibility;
- transparency;
- and discussability.

This will allow these values to be measured on a scaling chart, making it possible to compare organisations with each other. The code of ethics enables more direct reporting to the public and stakeholders of information about the organisation's biocircular goals.[40] The code of ethics also has a semantic-structural form, which offers a simple overview of the company culture. Currently, a semantic linguistic analysis of the ethical codes of institutions is still lacking, although initial attempts have already been made.[41] The code of ethics is not only a formal management tool but also fulfils ethical and aesthetic functions. A code of ethics is a general informal statement about the organisation's environment. Since this is a voluntary commitment, this structure is not given in advance. It is just a certain universal tradition. That is why most codes contain certain parts that follow each other. This structural standard usually includes the following individual parts:

- preamble;
- customer relations;
- relations with shareholders and other investors;
- employee relations;
- relations with suppliers;
- relations with competitors;
- connections to culture and local state authorities.

This form is not prescribed. It must be said that contemporary organisations often use different forms of reporting corporate culture in ethical codes (e.g. in the form of a brochure, graphically attractive visuals, etc.). More elaborated versions of ethical codes that are intended for the public, clients, or employees may also differ. But the form remains more or less the same, as ethical codes include provisions that make reference not only to the quality of products and services, compliance with local laws and regulations, and environmental protection, but also to the principles of transparency, fairness, and honesty. The relationship to trust in compliance with one's own set rules results from the overall social situation in a given state or business sector (e.g. a different relationship to ethical codes exists in the USA, the EU, or China, and a different relationship to ethical codes may exist in the banking sector, in the medical sector, etc.). However, unlike cultural or sectoral differences, the form remains globally similar. It is in this area that biocircular economic obligations can be presented very concretely. For the biocircular economy, there is an opportunity to be taken advantage of in making concrete commitments. What CSR (and, by extension, ethical codes) suffered from in general was vagueness and being highly theoretical. A biocircular economy with the possibilities of comparative metrics between organisations and with the high involvement of stakeholders can overcome these shortcomings.[42]

One of the first rules of a code of ethics is that every organisation has one clearly recognisable and definable code of ethics. The management of the organisation requires such ethical behaviour that it itself observes. It is possible for there to be multiple codes of ethics in relation to different groups. For example, the code of ethics for suppliers is different from the code for internal employees. But everything must meet the scope of one morality. There is no possibility that a double standard or double observance of morality would work.

One example is the different understanding of value between the culture of individualism (e.g., the USA) and the culture of collectivism (e.g. Scandinavian countries), when both cultures have a small distance to power within the intercultural dimensions in organisations according to G. Hofstede. In this regard, there is talk of contrast between the Scandinavian and American models of ethical codes: the Scandinavian model, in which employees actively participate in the detailed discussion and formulation of the corporate code of ethics; the American model, in which the ethical code is created by management representatives and company owners.[43] The principles of circular bioeconomic rules allow both models to be united within the main criterion.

4.3.3 The function of ethical codes

The influence of the code of ethics on management, the corporate environment, and stakeholders can be primarily direct. This means that the code of ethics expresses an effort to directly define responsible and irresponsible actions based on the unifying criterion of circular bioeconomics. Direct aspects can be dominant over indirect influences. These indirect effects can be assessed according to secondary aspects, how ethical codes affect not only direct stakeholders of level I (owners, management, employees) but also indirect stakeholders of level II (competitors, suppliers) or even stakeholders of level III (public, politics, experts). But these influences can have a significant effect on a certain sector of business. Among these functions, we can consider three basic functions: aspirational, regulatory, and educational (see Table 4.1).

The credibility of the ethics is ensured by the fact that the code of ethical conducts is also linked with other CSR tools in the organisation. Higher credibility of the code of conducts increases the connection with other CSR tools in the organisation (social projects, certification, and non-economic audits). For example, the ISAC methodology can be used to research the trustworthiness of the code of ethics, which serves as a quick guide to the typology of the code (Figure 4.4).

In the area of the circular bioeconomy, it is all the more true that the code of ethics must be linked to the company's specific organisational principles. The relationship between advantages and disadvantages must also be assessed in relation to the owners of the organisation. Cooperative or shared ownership of an organisation is a more suitable environment for the existence of ethical

Table 4.1 Three indirect effects of the ethical code of circular bioeconomic criteria

Function	*Content*	*Focus group*
Aspirational	Commitment to the future	Stakeholders I level
Regulatory	Rules of regulation not circular bioeconomic behaviour	Stakeholders I and II level
Educational	Innovative designs shape the pattern for the whole sector	Stakeholders I, II and III level

Source: own elaboration.

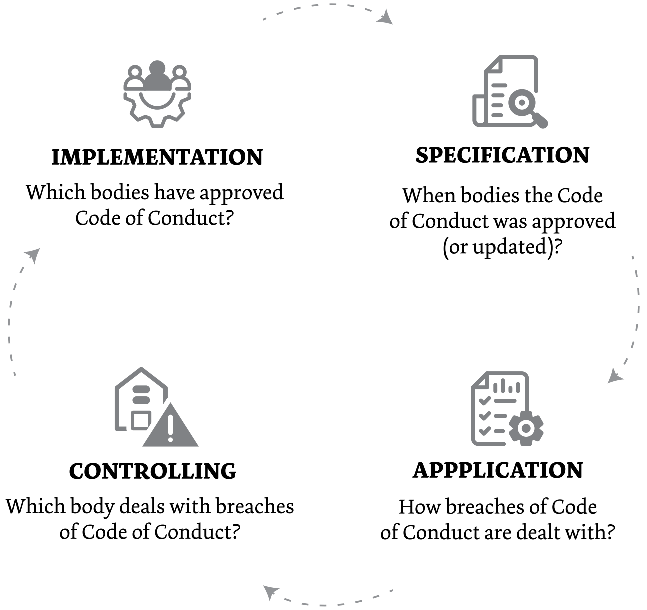


Figure 4.4 The ISAC method of gradual steps of implementing a code of conducts.

Source: Own elaboration.

Table 4.2 Advantages and risks of ethical codes in circular bioeconomic organisation

Benefits	*Risks*
• minimal implementation costs, immediate possibility of use in promotion, • rapid marketing communication, • increased attractiveness of company culture, • when revising internal documents, the basis for further development of CSR in the institution	• when a voluntary commitment is not respected, possible legal consequences follow from it – non-compliance with one's own commitment as a burden in the event of a dispute, • quick stakeholder review, • increased pressure to link with other CSR tools (certification, non-financial audits)

Source: Own elaboration.

codes. Small businesses with a local reach for managing ethical codes do not have such complex time and organisational conditions for approving ethical codes in accordance with the circular bioeconomy. Nevertheless, some basic benefits and risks can be observed (Table 4.2)

The circular bioeconomy, as a commitment to sustainable production and processing of biomass, contains in its genetic code the values that constitute responsible businesses. It is worth considering how these values translate into the construction of business models.

4.4 Circular bioeconomy business models

The business model should describe how the business creates and delivers real economic and social value. It is a tool that allows the executive team to experiment with different ideas and scenarios and predict outcomes in a safe, low-risk environment (Marsh, 2013, p. 11). Business models are concerned with how the firm defines its competitive strategy through the design of the product or service it offers to its market, how it charges for it, what it costs to produce, how it differentiates itself from other firms by the value proposition, and how the firm integrates its own value chain with those of other firms in a value network. In summary, a business model can be defined as a representation of business structures, in which all significant business phenomena are captured and their links are shown by the framework.

According to OECD,[44] the philosophy that underlies the circular bioeconomy business model is often referred to as "cradle-to-cradle" product design. This concept seeks to differentiate itself from the linear "cradle-to-grave" material flows, where materials within products ultimately end up in incinerators or landfills. Instead, these materials are regenerated and used as inputs in the production of new products. This approach draws parallels with natural systems, where the death of an organism contributes to the recycling of nutrients for other organisms. The adoption of circular bioeconomy business models is driven by two primary factors. First, replacing traditional inputs with renewable, bio-based or recovered alternatives allows companies to market their products as environmentally friendly. By differentiating their products in this way, adopting firms can target environmentally conscious consumers who may be willing to pay a premium for products with a reduced environmental footprint. Second, the transition to alternative material input helps companies manage regulatory and supply chain risks. Salvador et al.[45] identified that business model to be made of nine building blocks, which are (1) customer segments, (2) value proposition, (3) channels, (4) customer relationships, (5) revenue streams, (6) key resources (7), key activities, (8) key partnerships, and (9) cost structure. In contrast to traditional business models, there is a need for circular business models of the bioeconomy that focus on resource lifecycles and efficiencies which involve actors beyond the company itself. From a practical perspective, the implementation of a bioeconomy is still lagging, and companies are struggling to develop effective business models.[46] One of the key challenges is designing business models in such a way that enables the firm to capture economic value for itself through delivering social and environmental benefits.[47]

The literature on the topic of bioeconomy business models is relatively extensive and describes various solutions based on:

- Industrial symbiosis
- Eco-design to reduce material leakage and/or eliminate waste
- Recycling

- Utilisation of renewable resources
- Upcycling and cascading
- Energy recovery
- Take-back system: manufacturers and sellers take back products that are at the end of their life cycle in order to reuse, recycle or recover them and put them back on the market as a new product.
- Product-service system: provision of goods and services that are designed and combined in such a way that together they are able to fulfil specific customer needs, build unique relationships with customers, strengthen customer loyalty and innovate faster than goods and services in the conventional business models.
- Strategic partnerships between bioeconomy players[48]

In their excellent study, R. Salvador, F.N. Puglieri, A. Halog et al.[49] distinguishes the most important building blocks that make up business models in the bioeconomy (Figure 4.5).

Bröring and Vanacker[50] present a different approach to the theory of business models in the bioeconomy. The specificities of the bioeconomy, such as the complex knowledge base, fragmented policy systems and different types of

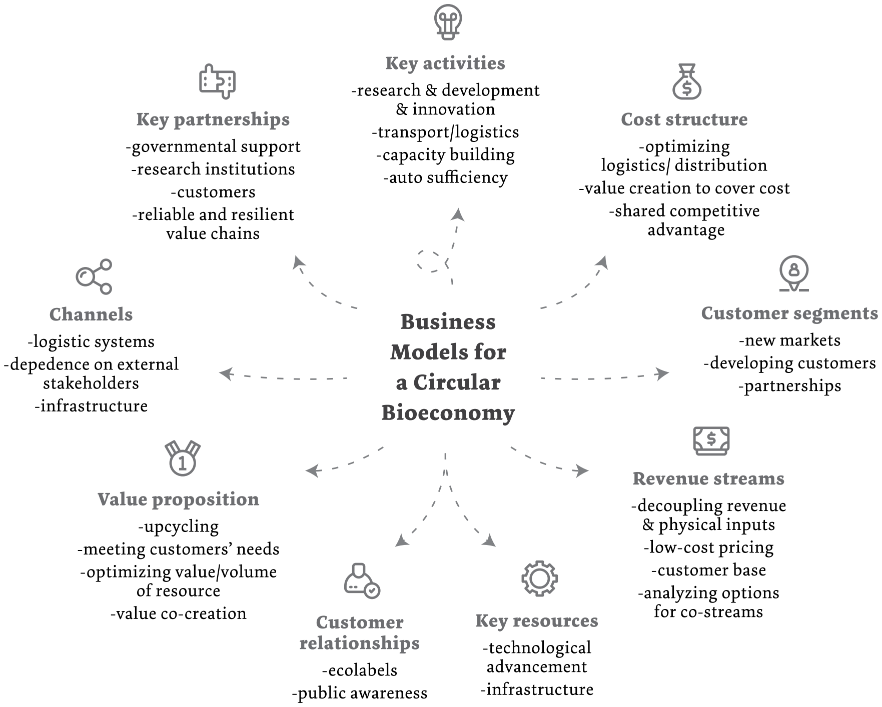


Figure 4.5 Main areas that build business models in the bioeconomy.

Source: Own elaboration based on R. Salvador, F.N. Puglieri, A. Halog et al. (2021).

innovation, lead to a number of challenges for business model development in the areas of technology, market, value chain, product quality and availability, geographical and spatial issues related to biomass logistics, economics, policy and regulations, and organisation. The authors embed business models in innovation categories (see Chapter 5) and characterise business model types based on their value proposition for stakeholders in the value chain.

- The first business model is based on the production of a substitute product for an existing product that is based on non-renewable resources. This creates added value for the consumer, who receives an environmentally friendly product, but also for new partners who supply biomass and contribute to value creation. This model can apply to biofuels and mass-produced products, but also to bio-based alternatives to plastic. Sourcing an adequate amount of biomass could be a challenge, as well as consumer prejudice and low product.
- The second business model is characterised by bio-based products that have new functions. Their manufacture is associated with a new production process and thus with new roles in the value chain – from the supply of biological raw materials to the marketing and communication of the new product. This type of business model often implies the integration of new knowledge into the company or the combination of knowledge from different areas, which leads to organisational challenges. Product innovation can pose problems in the context of regulations that do not provide solutions for this type of product

Case study

MakeGrowLab for a global market

One example of the second type of business model is MakeGrowLab (MGL) (https://www.makegrowlab.com). It started in 2016 with a question: what if we could use local raw materials to produce renewable and versatile materials instead of producing them using traditional methods? The first experiments focussed on cellulose obtained from the kombucha brewing process, but it turned out that its mechanical properties were not suitable for commercial production. Despite this initial failure, the project founders did not give up and after years of trial and error developed Scoby packaging materials – durable, fully compostable and plastic-free.

MakeGrowLab uses its own technology to produce SPM® – bacterial nanocellulose (BNC) nanofibres. Using the patented process, the company is able to obtain cellulose with unique properties that surpass traditional methods of obtaining plant cellulose. The key element that characterises the MakeGrowLab process is its circularity, which does not require the use of chemicals, wood or large quantities of water. This ecological approach enables the production of nanocellulose with high purity and excellent mechanical properties. MakeGrowLab minimises the consumption of natural resources and reduces the impact on the environment. SPM® nanofibres are characterised by high strength and durability as well as a variety of other beneficial properties. Nanocellulose has a larger surface area in relation to its volume, which increases its effectiveness in various applications. The material itself has a higher tensile strength and, in addition, the production of nanocellulose is more cost-effective and energy-efficient.

SPM® nanofibres are characterised by low emissions, a high biocomponent content and efficiency. Packaging materials made from these fibres are lighter and stronger. The coatings and films of SPM® technology act as a barrier against oxygen, grease and water vapour and are insoluble in water, making them an ecological alternative to conventional plastic packaging. SPM® nanofibres can be added to paper and pulp to improve their physical and barrier properties. They are used in many areas. They can be used to produce biodegradable, completely safe coatings suitable for contact with food or cosmetics, but also to improve products in these areas, as a low-calorie fibre or as a moisturiser in cosmetics.

Thanks to the use of microorganisms in the production process, MakeGrowLab is able to obtain pure bacterial cellulose. The process eliminates the environmental pollution typical of processing plant cellulose, requires much less energy and largely dispenses with the use of chemicals and requires much less space and time than conventional methods of producing and processing plant biomass. This makes production more ecological and sustainable. MakeGrowLab utilises biological waste from agriculture, food and forestry.

- The third type of business model is based on the product-service system. The value proposition for the customer can therefore be an additional service to the purchased product or the use of the product without ownership rights. In this model, communication and the relationship with the customer take centre stage. In addition, the company’s internal structures must be adapted to the sale of services, e.g. in a separate business unit.

Case study

Veggies War for a local market

- One example of the third business model is a subscription sale of food in a short distribution chain. One of the companies implementing this model is Veggies War (www.wojnawarzyw.pl). The model is based on several values and assumptions:

- Reduction of food waste – At the distribution stage, food waste is reduced to zero. Vegetables offered for sale may deviate from the ideal shape, size and lustre; they may have a short shelf life. However, these are valuable products that would probably not be sold in conventional trade.
- Short distribution channels – most products are supplied directly by local farmers.
- Use of only biodegradable packaging.
- Easy contact and user-friendly application for individual purchases or subscriptions.
- Possibility to subscribe to deliveries of vegetables and products from local farmers directly to the consumer. At regular intervals determined by the customer, they receive the products they have subscribed to or a surprise box with products that are currently on sale.

To summarise, there are several elements that distinguish circular bioeconomy business models from conventional models:

- Environmental responsibility: A strong dependence on ecosystem services that support the production and processing of biomass. This means that greater environmental responsibility is built into the DNA of the business. The use of renewable raw materials is an expression of this concern for the environment, but at the same time the health of the ecosystem is a guarantee for the production of the raw materials necessary for production.
- Innovations: Strong link to innovation both in biotechnology and in the sustainable production of primary biological resources.
- Social responsibility and local context: A new context for relations with stakeholders. The development of bio-business requires cross-sectoral cooperation to optimise the circulation and use of biological resources. Collaboration with research and development organisations can be a key element for the market success. The bioeconomy has a stronger connection to local communities and can (or should) be more dependent on local bio-based resources. It implies a need for greater social responsibility.
- Complex value chain: A complex and highly interdependent value chain that includes the following: Production of biological raw materials, their collection and pre-processing, processing and production processes, logistics, consumption, utilisation of residues of bio-based products and management of their further life cycle or reintroduction into the planet's metabolic cycle.

4.5 Project management in bioeconomy

Circular bioeconomy projects range from pure research concepts (e.g. experimenting with new materials for batteries) to major infrastructure investments (e.g. transforming waste management in cities) and relate to all industries and operations that currently use or could potentially use biological resources. The common denominator in most definitions of this type of projects is innovation.[51] The objectives of such initiatives are primarily oriented towards environmental improvements with impact on people's quality of life, but the goal is also to achieve tangible economic benefits.[52] Bioeconomy projects are based on technological innovations (Industry 4.0), but are also dependent on business aspects and socio-technical systems. Currently, there are many initiatives in biofuels, forestry, food industry, chemicals, biopolymers, biomaterials, bioprocesses, biotech crops, biorefineries, and biodiversity conservation (Bauer, Hansen, Hellsmark, 2017). They are often exploratory and need to address expectations from several different dimensions, including societal and environmental goals, consumer behaviour, economic factors, technical viability, etc.

According to Watt, *in addition to considering the cost, scope, and schedule of a project, a project manager should work to ensure the project is socially, responsible, environmentally sound, and economically viable*.[53] As Figure 4.6 shows, management of a project relating to the circular bioeconomy, in addition to the standard management tasks, must also take into account sustainability and innovation aspects, the importance of which are emphasised by scientists involved in bioeconomy and biotechnology.

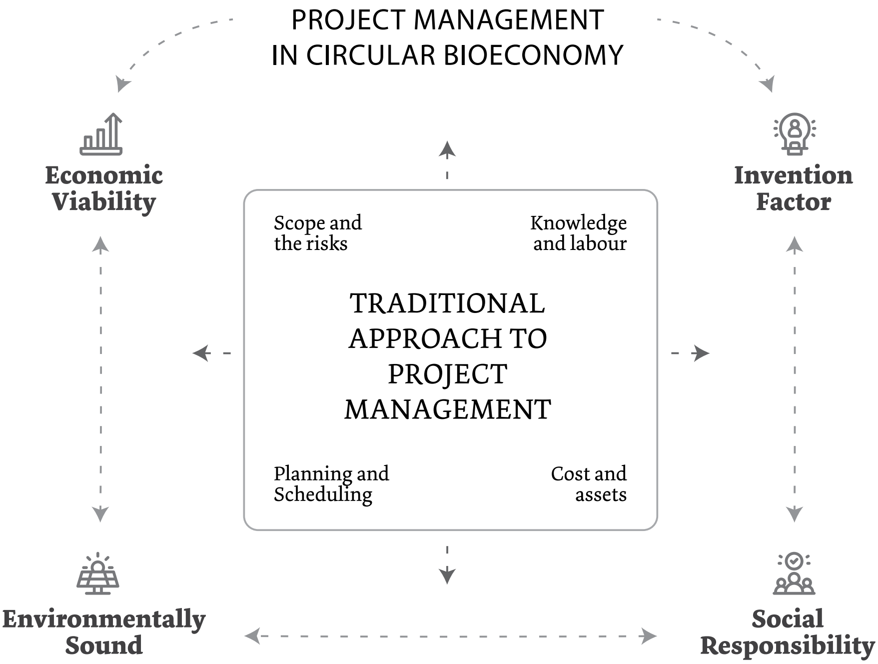


Figure 4.6 The factors most relevant to circular bioeconomy projects.

Source: Own elaboration

There are many definitions of a project. It can be generally accepted that a project is *a unique set of events with a main goal and defined objectives, as well as agreed plans for achieving that goal.*[54] When specifically considering circular bioeconomy projects related to research, it has been found that they tend to focus mainly on *the creation and diffusion of techno-economic knowledge*,[55] e.g. technological applications and market acceptance; and to a lesser degree on systems knowledge, e.g. handling of risks and undesired effects. Referring to bioeconomy projects, Van Lancker et al.,[56] state that such projects "*require radical and disruptive innovations, based on complex knowledge base* and *[co]operation between organisations from different value chains*". Examples include projects aimed at innovative techniques of reducing waste heat, projects implementing their own sources of energy (not only in the countryside but also in cities), or projects reducing harmful emissions.

Case study from Sweden

Regional Circular Economy Center in Sweden[57]

Background: The project deals with the creation of a regional resource center together by several already existing stakeholders, i.e. it is mostly about network and capacity development.[58] Five organisations work together in this project (September 2023–August 2027): Vreta Kluster, Cleantech Östergötland, Regions of Örebro and Östergötland and Innovative Materials Arena. Project goals include supporting companies (small and medium-sized) in finding and using possibilities for the more efficient use of resources and closing of resource loops as well as supporting municipalities and other local actors so that they can contribute to a transition to circularity in the economy.

Project managers' (PM) view:

- The project aims to facilitate networking for cooperation around more efficient resource use; bioeconomy and industrial symbiosis are two main focus areas,
- Concrete goals are still under development; funding agencies have required certain indicators to be reported (e.g. how many activities are organised and how many participants they attract); ongoing external evaluator (from a consultancy firm) that focuses on goal-setting and measurability will be supporting the project,
- The five participating organisations in the project have different needs and therefore somewhat different views on goals; the process of goal-setting is difficult to speed up; the organisations have a lot of experience and competencies but are used to working independently,
- PM considers the project as agile and finds it important to balance between being concrete vs. being open about project activities and goals; balance also important in PM's role – steering vs. stimulating creativity,

- PM currently sees *finding a common agenda* between the participating organisations as the main challenge/risk; the project is very much about *soft activities* such as meetings and matchmaking that can be difficult to manage since they involve interactions between people.
- Another challenge is contributing to identifying and seizing opportunities that can be found in resource flows between organisations but also supporting organisations in creating formal legal agreements that create greater security for involved parties,
- During the startup of the project the PM held a two-day workshop with the participating organisations: day one focused on project structure, while day two focused on the project team. This first workshop was successful; however, the next meeting after that was more confrontational with different views on roles and expectations becoming visible among participants. E.g. there were different views on how to distribute responsibilities related to the project's eight work packages. Also, there were different views on what the PM should do – only administrative and reporting or a more steering/driving role?
- PM considers building a project team and forming a message that can reach out to the surrounding community and businesses as her most important tasks, along with creating a structure that participating organisations can work within towards a common agenda.

On the base of the presented case study and literature review, some phases in the management of this type of project can be distinguished: 1) initiation, 2) planning, 3) execution, and 4) evaluation (closure).

In the initiation phase, ideas are generated, the context of the problem is defined, data and information are obtained from various sources, and a diagnosis of the problem is made. Based on the information and ideas gathered, the best solution (idea) can be selected and its implementation planned. Bioeconomy projects often require the involvement of "users" or stakeholders in the process of design of a service or product (UCD – User-Centred Design). It is vital to answer the following questions:[59] Why is the project worth implementing and which of the SDGs can be achieved? What is the context (including local) and who can be potential beneficiaries/stakeholders? What are the existing policies and regulations that affect the project? How can its value (both financial and non-financial) be determined? What is the technical and organisational design of the new solutions? What are the main problems and opportunities related to the project? Does the organisation/company/institution have the technical and human capacity and the knowledge to meet these needs?

Different ways of defining the project or finding new solutions can be used in the initiation phase, e.g. the Waterfall model, the Agile approach or the Design Thinking method.[60] When defining the problem, it is useful to use creative thinking methods, for example: the "5 Why" method, the Ishikawa diagram, the problem ladder, ideation, brainstorming, de Bono's 6 hats method, lateral (inverted) thinking, Mind Mapping, Scamper (modifying existing solutions in different ways), prototyping (physically designing a product or solution, in the form of a model), etc.

The initiation phase is accompanied by many uncertainties that arise from the process of seeking information, knowledge and project ideas. Many factors must be taken into account at this stage. Figure 4.7 highlights those factors that are particularly important in the initiation of bioeconomy projects: within policies, strategies and legislation, one should have an understanding of environment, trade, energy security, genetically modified organisms and R&D, agriculture and waste legislation. The driving forces can come, however, from both the surrounding environment (business or global environment) and internal sources (organisation). Such driving forces often include a need for renewal of traditional industries where bioeconomy is seen as a way to future-proof the organisation. Bioeconomy projects also address societal issues, such as employment and economic competitiveness, food security, natural resources management, dependence on non-renewable resources and climate change mitigation. One non-renewable element is the use of resources (land, labour, natural resources) in a sustainable manner.[61]

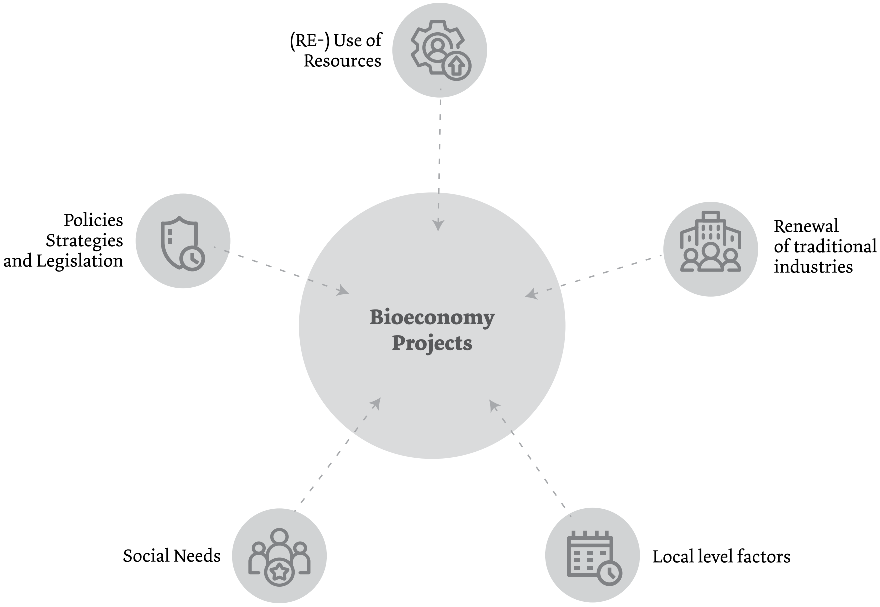


Figure 4.7 Key factors influencing the initiation of circular bioeconomy initiatives.

Source: Own elaboration based on: Van Leeuwen, M. et al. Overview of WP1 in the EU FP 7 SAT-BBE project: Systems Analysis Tools Framework for the EU Bio-Based Economy Strategy, Wageningen University 2013 and Bioeconomy: EU is moving towards its goals, but environmental challenges persist, EU Science Hub, Joint Research Centre 2023.

The next stage is planning and shaping the project. At this stage, the visions and goals of a circular bioeconomy project should be defined. The products or services that will result from the implementation of a such project must be oriented towards Sustainable Development Goals, but should also be user-oriented (with the user defined as customers, residents, community, etc.).

The project planning phase ends with a detailed plan that describes the scope of the project, the role of a project manager, the tasks of the team members or staff, the communication plan, and the criteria for success.[62] It is also necessary to clarify and specify the details and prepare a time and financial framework on which the project will be based. At this stage, a SIPOC (suppliers, inputs, process, outputs and customers) table can be used to define the scope of the project and its expected results.[63] During the project preparation phase, it is also necessary to establish a timetable, a work structure and a list of tasks and to identify the people responsible. The Work Breakdown Structure (WBS) matrix can be used to concretise the work in the project, as well as a Gantt chart. Also important at this stage is the setting of milestones, i.e. specific points on the project timeline that are relevant for evaluating progress towards project goals.

In order to manage the project staff well, it is important to break down the roles and tasks as well as to establish the scope of each person's duties and responsibilities. In carrying out the team management functions, the PM can draw up a roles and responsibilities matrix, or use other available methods, such as the Responsibility Assignment Matrix or the RACI matrix often used in the process approach.[64]

The execution phase is the implementation of actions, i.e. the execution of the tasks that have been planned. This phase includes the processes of managing the team and monitoring progress. The manager is responsible for organising and conducting meetings. Information can be communicated through various channels. The most common are verbal and written channels. The verbal channel allows for a direct relationship with employees, while the written channel enables a permanent record to be kept or is used in situations where the message contains a lot of content or detail.[65] In general, direct methods (meetings, phone calls) and indirect methods (emails, letters), using ICT tools, are employed to convey information. For time management, schedules in graphical or textual form are used, e.g. based on the Gantt chart or IT systems such as Microsoft Project, Asana or Jira. The Crashing method, PERT or simple Kanban board also can be used in time management.[66]

It shouldn't be forgotten that bioeconomy projects are characterised by realistically higher risks, both external and internal, as they are accompanied by entirely new challenges.[67] There may be problems e.g. with material efficiency: quality or availability of raw materials. Bioeconomy projects could also entail risks related to unintended consequences, such as changes in land use and threats to biodiversity that, for example, could be observed with regards to biofuel production.[68] Some factors/risks can result from market conditions, but they may also arise from institutions or market regulators. Various monitoring methods are used to identify risks of an internal or external nature, including observation, interviewing, record keeping, modelling, Delphi method or brainstorming.

The last phase: evaluation (closure) is also very important, especially in the context of bioeconomy initiatives. The bioeconomy refers to new regulations and processes in economies, shaping new solutions, a new market for products and services, which requires advanced knowledge and people with specialist expertise. Hence, a project in the area of the bioeconomy should be a coherent concept, the implementation of which corresponds to the overall directions of development and activities of the bio-based solutions economy, with sustained effects.[69] Concerning this aspect of the bioeconomy projects, it is important to evaluate the results obtained with the objectives (Sustainable Development Goals), including, above all, determination of the impact of the project on social development (in its various dimensions), on economic development and on the environment through sustainable economic development.[70]

Business entities involved in the circular bioeconomy initiatives face a number of new challenges, notably in meeting the SDGs and CSR targets, as well as in finding new pathways for innovative projects and implementing new business models. Managing such projects requires project managers to take a holistic approach and gain knowledge from different sources. Also, as indicated in the example of the Swedish case study, collaboration between multiple actors and sectors is crucial, especially between customers, suppliers, regulators, NGOs and communities. The importance of building social trust is also emphasised, as well as the creation of so-called cluster networks of different entities to implement projects related to bioeconomy transition.[71] Consequently, business entities and organisations need to invest in such resources and capacities if they aim to drive development towards the bioeconomy.

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58 Connection to the literature: Jansson & Ljung model of four sources of uncertainties (p. 154–159): 1) Complex project structure, 2) Degree of novelty inherent in the project, 3) Driving forces and different views on goals, trust deficiency, 4) Fast-paced changes in the surrounding conditions. The Swedish project relates very much to number 3, in such situation authors suggest focusing on driving forces and views first and foremost, before creating an operative plan. They suggest working with openness to overcome mistrust and suspicions; finding common ground and meaningfulness that relates to all involved actors; creating arenas for meeting each other and working together. More on: www.energikontoretostergotland.se.

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Part II

Interdisciplinary links in the bioeconomy

Innovation, environment and product

5 The circular bioeconomy and innovation

Michał Niewiadomski, Piotr Waląg and Małgorzata Pink

5.1 Introduction

The bioeconomy may provide a partial answer to problems related to climate change, resource shortages and achieving economic growth while using limited resources. It embraces the efficient production and use of biomass and biological processes, and is based on economic policy strategies that aim to create new jobs, develop technologies and combat resource scarcity.[1] The emergence of the circular (bio)economy paradigm can be considered to herald socio-economic change comparable to that of the Industrial Revolution, which disrupted links between people and natural cycles introducing mass production, whilst also liberating societies from consumer shortages, changing the landscape and securing existence through processes of urbanisation. The price of progress was paid in the form of external costs, with a negative impact on natural cycles, such as the carbon, nitrogen and phosphorus cycles, which are the source of today's climate crisis. Finding a way to maintain social well-being, while eliminating external effects appears to be a necessary condition for society's survival. This change requires 'creative destruction', so in this context it is worth citing J. Schumpeter's theory of innovation, in which he described a process where innovation and technology contribute to economic progress, but at the same time lead to the disappearance, destruction and obsolescence of technologies and business models, which may, in turn, bring about the collapse of certain businesses or sectors of the economy.[2] It seems that we are witnessing such a process, in the broad sense, in line with long-term Kondratieff cycles (Figure 5.1).

Although considerations about innovations lifting the economy to a higher level are to some extent speculative, it is already possible to indicate that the sixth Kondratieff wave, which began around 2010, will be driven by technological change, enabling more efficient use of resources, the creation of new energy systems, digitalisation and the circular (bio)economy. However, with reference to the seventh wave, which should come during the period from 2050 to 2100, M. Wilenius writes:

DOI: 10.4324/9781003453529-7

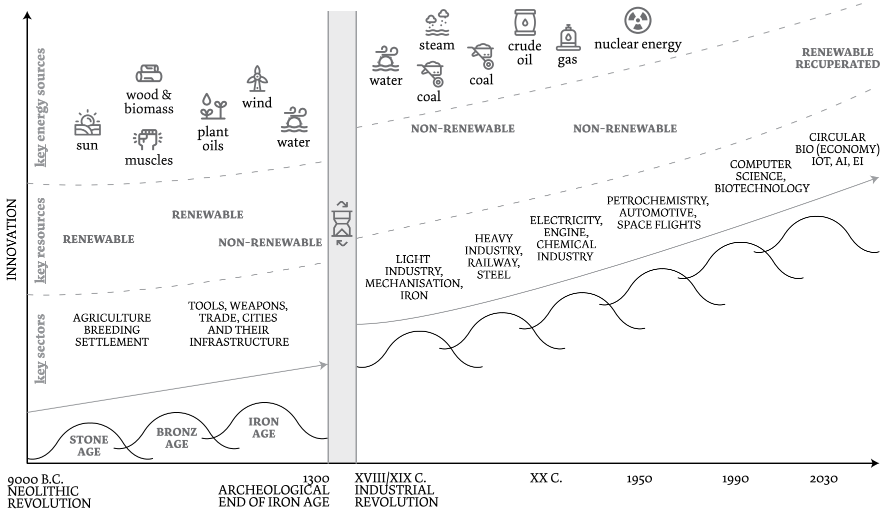

Figure 5.1 Evolution of socio-economic development taking into account the phenomenon of cyclical nature of the economy and the assumptions of Schumpeter's theory.

Source: Own elaboration based on Clarke, T. and Hilbert, M.[3]

> *A changing world is moving from climate shock towards a rebalancing of resource use and resource renewal. Industrial heritage systems have been superseded by biological systems (…). In the oceans (…) kelp forests are now exploited for a variety of goods and services. (…) People are refining organic materials, and the entire planet has been turned into a garden that is carefully nurtured and harvested. (…) The bioeconomy has become the new economic paradigm, coupled with advanced concepts of circulation and social equality.*[4]

The emerging framework of the circular (bio)economy is, for now, an innovation in itself, in the context of Schumpeter's conditions of innovation.

Though circularity is an immanent characteristic of nature, for the modern economy the circular (bio)economy model is an innovation. Its ideological assumptions force changes in existing economic structures, destroying inefficient or environmentally harmful practices and making room for new, more sustainable approaches, which is an example of 'creative destruction'. As a result, changes are occurring both in the structure of the market, posing a threat to existing sectors and products (e.g. conventional, mass-production agriculture and breeding; the fossil fuel industry, petroleum products) while at the same time creating new product possibilities and new business models, and in the structure of the economy, by transforming existing standards of production, consumption and management of side streams and by-products. These processes are in themselves an effect of technological progress, and the changing structure of the economy forces stakeholders to look for innovative ways to adapt to these changes. In this way, the bioeconomy, constituting innovation, drives the innovative activities of stakeholders. Apart from the technological context of innovation, changes in society's approach to production, consumption and economic goals are a condition for the consolidation of new economic structures. Social innovations, which may involve conceptual, process, product, organisational and relational changes, improving the well-being of individuals and communities, are thus equally important.[5] At the meta level, however, they are related to changes in social values and redefining the goals of economic activity.

5.2 Innovation in the bioeconomy

During the pre-industrial period, practically the whole economy was biologically based. In itself, there is nothing innovative about a return to biological raw materials. It only becomes innovative when biomass is put in a new context. Bröring et al.[6] attempted to identify types of innovation in the bioeconomy (Table 5.1).

Table 5.1 Innovation types in the bioeconomy

	Innovation type	*Characteristics*	*Examples*
I	**Substitute products**	Innovations as a substitute for fossil fuel-based products. May be integrated into existing value chains. Product is innovative, but does not offer any new functionalities. Non-disruptive.	• Biodiesel • Bioethanol PLA
II	**New processes**	Changes to the entire value chain of bio-based production. Creates new value chains or new connections and combinations in existing value chains. Disruptive.	• Genetic engineering of plants • Use of new biomass (e.g. microbes, fungi) to produce enzymes, chemicals Products similar to type I insofar as they are associated with the disruption of conventional value chains
III	**New products**	Completely new bio-based products with radically new functionalities. Open up opportunities that lay beyond existing value chains. May have an impact on the creation of further innovations and completely new value chains. Disruptive.	• Artificial microorganisms producing specific active substances for medical purposes • Bio-based and biodegradable materials used in surgery and medicine, more biocompatible with the human organism Use of bioluminescent organisms to light cities or homes.

(*Continued*)

Table 5.1 (Continued)

	Innovation type	*Characteristics*	*Examples*
IV	**New behaviours**	Changes in the way customers expecting bio-based products behave. Consolidation of new cascading or circular business models. Implementation of servitisation of bio-based products. Development and realisation of collaborations with external stakeholders e.g. academic institutions, civil society.	• Effects of Horizon projects with the aim of implementing the bioeconomy and raising awareness of it among stakeholders in external economic entities. • Waste recycling and collection systems in cities and conscious engagement of residents Conscious use of by-products for further production processes

Source: Own elaboration based on: Bröring, S., Laibach, N., Wustmans, M.[7]

The innovations listed in Table 5.1 are characteristic of the bioeconomy, but at the same time they also concern specific sectors, in which individual products and services either are changing or are bringing about change in the behaviours of market entities. Evolution towards the circular (bio)economy takes place through the transformation of individual sectors and social transformation. The circular (bio)economy should be perceived as a way in which socio-economic reality as a whole functions, not as a tool used in isolation or an additional instrument of the green economy understood in the broader sense. The circular (bio)economy is a comprehensive economic model, merging many sectors (Figure 5.2).

Figure 5.2 only schematically refers to sectors which function in the sphere of the bioeconomy, and also refers only to the production context. Certain of

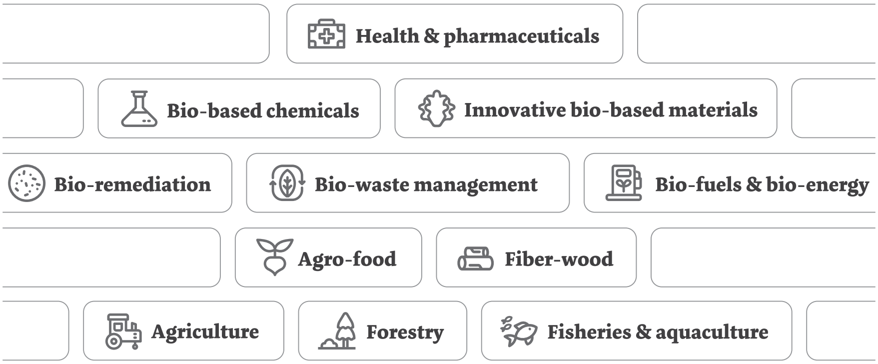

Figure 5.2 Key sectors of the bioeconomy.

Source: Own elaboration

the sectors shown have been meetings our needs since the beginning of civilisation, and a bioeconomy based on ecosystem services is founded in the deepest relationship connecting humans with reality – namely a biological relationship. The bioeconomy, understood as a part of the circular economy system, depends on innovation based on numerous mechanisms which have already been observed and described (Table 5.2).

In summary, the circular bioeconomy understood as an economic model is the result of evolution of the economy and, as such, is an effect of an innovative way of thinking. The capacity to generate innovation is written into its genetic code, and, in this respect, it is no different to the known economic models of the 19th and 20th centuries. However, perhaps its advantage will prove to be a natural tendency to create networks of connections that strengthen its innovative potential.

Table 5.2 Selected generations of innovation processes and their properties

Selected generations of innovation processes	*Properties*
First-generation innovation processes. Technology-push	Technology has an influence on the creation of innovations and R&D plays a key role in this phase. In the context of the bioeconomy, this is above all concerned with the dissemination of industrial biotechnology, enabling the use of living organism and materials derived from them for the mass production of industrial goods.
Second-generation innovation processes. Market-pull	Conscious consumers wanting to put the principles of clean production and consumption into practice in all sectors of the bioeconomy. • Consumers of seed, plant protection agents and agricultural support, and thus entities responsible for primary production in the bioeconomy, whose expectations change together with increased awareness and also with external transformations – climate change, soil degradation, growing need for food and biomass, etc.
Third-generation innovation processes. Coupled	• Coupled model combining innovation processes of types 1 and 2. Was described in the context of limitation of access to resources in times of oil crises as an alternative to models 1 and 2, which did not describe reality. It is possible to put forward the hypothesis that the current climate crises puts the bioeconomy in a similar position. Innovations in the bioeconomy seek to meet the expectations not only of consumers, but also, more broadly. of stakeholders too, not only helping to maximise the utility of the economic entity, but also benefiting the social and natural environment. Biotechnologies and biomass production technologies focus on both market and non-market goals.

(*Continued*)

Table 5.2 (Continued)

Selected generations of innovation processes	*Properties*
Sixth generation of innovation systems. Self-learning systems	• They focus on the integration of systems and networks to guarantee flexibility and rapid development. The process creating innovation involves reaching for external and internal ideas. It is linked with the sharing of risk and rewards and allows innovators to obtain external feedback. The circular bioeconomy, by creating networks of raw material connections, involves a large number of stakeholders who interact with each other, thus also becoming part of the sixth generation of innovation systems.

Source: Own elaboration.

5.3 Can the circular bioeconomy become a mechanism to drive innovation?

Will the circular (bio)economy, by becoming a production paradigm, be as revolutionary as the Industrial Revolution of the 18th and 19th centuries? Such an assumption may open the way for a somewhat speculative comparison with the processes that were accurately diagnosed in the mid-20th century by the French economist and politician Jean Fourastié.

5.3.1 Fourastié's model and implementation of the bioeconomy

In 1949, Jean Fourastié presented a theory of economic growth based on technological progress, noting that technological progress (for the purposes of this chapter identified with technological innovations) enables an increase in productivity measured by the ratio of production volume to the number of hours of work, but this effect is not homogeneous over all sectors and over time.[8] Based on these differences, he distinguished between the following sectors:

- The primary sector, mainly agriculture, characterised by medium technological progress.
- The secondary sector, mainly industry, experiencing rapid technological progress.
- The tertiary sector, mainly services, experiencing low technological progress.

Analysing consumer behaviour, Fourastié proposed a hypothesis which envisaged the saturation of demand for food (to which Engel's law[9] also makes reference) and, at a significantly later stage, saturation of demand for industrial goods, together with progress in national economies. The services sector is characterised by an absence of saturation. In around 1800, around 80% to 90% of the active population worldwide were employed in agriculture. 150 years later, only 20% of the active population worked in agriculture in developed countries. According to Fourastié, the level of technical and technological innovations, measured in terms of productivity, is responsible for rural depopulation. Strong differences in the level of technical and technological innovations and the productivity of labour dictated by it are responsible for differences in the level of development of the economy between highly developed and less developed countries. Demand and capacity for innovation are thus the two main determinants of the level of employment in agriculture in the economy. This phenomenon is shown in schematic form in Figure 5.3.

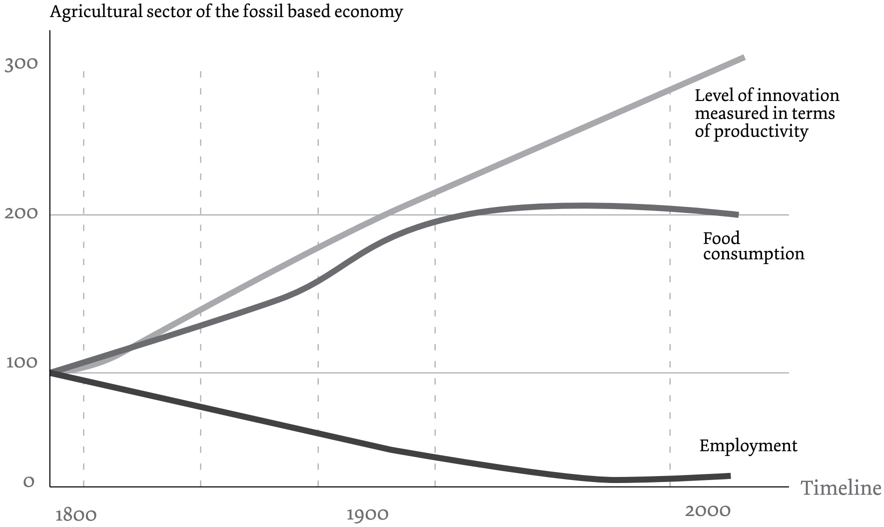

Figure 5.3 Relationships between productivity (index of innovation) and the level of food consumption and employment in the agricultural sector.

Source: Own elaboration based on Jean Fourastié.[10]

The phenomenon of a decrease in employment in agriculture in relation to meeting demand for food is characteristic of highly developed countries. However, in the bioeconomy, the primary production sector – agriculture, fishing and aquaculture, forestry – takes on the role of the traditional industrial sector and takes over functions of the extractive industry, replacing fossil fuels with biomass (Figure 5.4).

At the current level of development of civilisation, demand for energy and other goods from the industrial sector is not at risk of stagnation. One of the energy raw materials is biomass. So if the demand for biomass in industry,

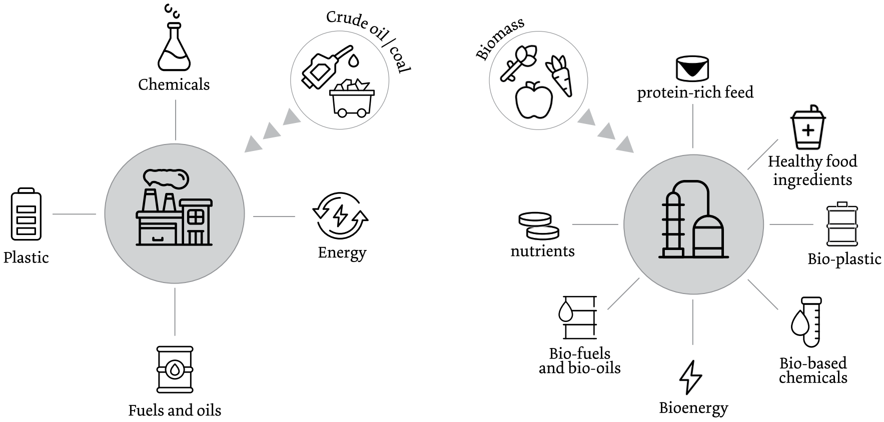

Figure 5.4 From conventional refineries to biorefineries.

Source: Own elaboration, based on Pink M., Wojnarowska M., (ed.) Biogospodarka. Wybrane aspekty (Bioeconomy. Selected aspects) Difin, Warsaw, 2020.

together with the development of the bioeconomy, is going to rise steadily, and at a higher rate than the growth in productivity driven by the increase in the level of innovation in the agricultural sector, employment in the sector should rise. The initial phase of development of the bioeconomy, by analogy to the fossil fuel-based economy, justifies making such an assumption (Figure 5.5).

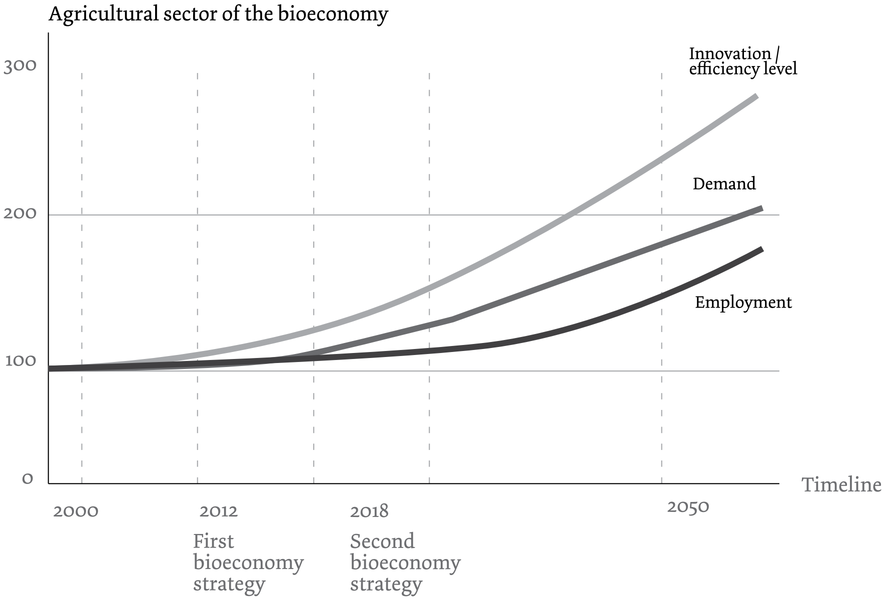

Figure 5.5 Relationship between the level of employment, capacity for innovation and demand for biomass in the bioeconomy.

Source: Own elaboration.

Growing demand for biomass in the bioeconomy, in contrast to the saturation of demand for food in the fossil fuel-based economy, leads to an increase in the level of innovation (measured in terms of productivity), resulting in the expected rise in employment in the primary biomass production sector. A similar phenomenon was observed in the early stages of industrialisation, when the rapidly increasing rate of demand for industrial goods coupled with the slower rate of growth of productivity of industry in the economy led to rise in employment in that sector (Figure 5.6).

The turn of the 19th and 20th centuries saw the rapid development of science and numerous inventions which resulted in strong growth in productivity in industry (e.g. the electric motor, the telephone, the light bulb). Over time, the growing rate of growth in productivity started to overtake the rate of growth in demand for industrial goods, leading to a situation where production started to exceed demand. Then, as in the case of agriculture, the employment equation is opposed to the productivity equation and begins to decline, which ultimately causes the employment curve to tend towards an asymptote of 0. Change in the level of employment (Figure 5.6) is the ratio of change in demand for goods to change in productivity for those goods $\Delta D/\Delta W = \Delta Z$.[11] Assuming that productivity is the ratio of change in the volume of production to change in the level of employment $\Delta Q/\Delta Z = \Delta W$,[12] it can be said that the condition of balance of supply and demand means that higher growth in ΔD than growth in the ratio $\Delta Q/\Delta Z$ results in a rise in employment, in the case of growth in production. However, lower growth in ΔD than growth in

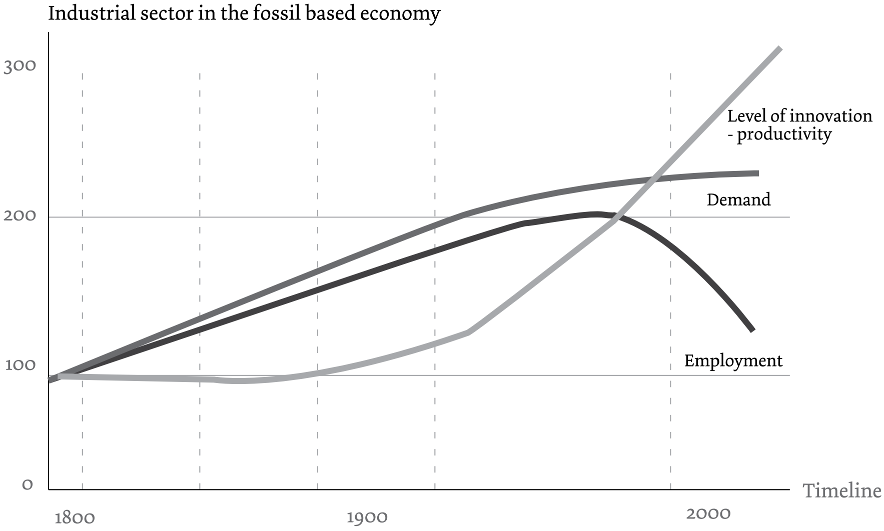

Figure 5.6 Level of innovation measured in terms of productivity, demand and employment in relation to one basic reference product in the industrial sector or for the whole sector of industry in the fossil fuel-based economy of highly developed countries.

Source: Own elaboration.

the ratio $\Delta Q/\Delta Z$ results in a fall in employment, even in the case of growth in production.

In industry, the trend of change in productivity is a growing one, as technical progress has the strongest effect. The constantly growing difference between the trend in growth in productivity and the trend in growth in demand causes employment in industry to start to fall, as the volume of industrial production starts to surpass the stabilising volume of demand starting the phase of deindustrialisation.

5.3.2 The industrial sector and disappearance of innovation

In recent decades, studies of the evolution of economies have found evidence of three important phenomena:

- premature deindustrialisation,
- jobless growth of industry in the formal manufacturing sector,
- faster growth in services than in industry.[13]

The negative phenomena mentioned above may be partly responsible for hidden unemployment and the shift of human capital to low-productivity sectors of industry and the provision of services on the grey market.

In the economies of countries finding themselves in the medium-income trap, in which these phenomena occur, a low level of innovation is observed, manifesting itself as the production “potato chips not microchips”.[14] According to Nicholas Kaldor, analysing the importance of individual sectors of the economy for economic progress, the rate of growth in productivity in the economy as a whole depends on expansion of the industrial sector. The rate of growth of innovation is fastest in industry, determining the development of that sector. According to Verdoorn’s law, faster growth of production leads to an increase in productivity as a result of growing effects of scale and has a spillover effect (growth in productivity) on the whole economy.[15] Growth in the rate of productivity in the economy as a whole also depends on the shrinkage of decreasing returns of scale and inefficient economic activities. The release of labour and other resources from inefficient activities (characterised by decreasing returns of scale) and their shift to the dynamic manufacturing sector has a double gain for productivity growth in the economy as a whole: it increases productivity by releasing surplus labour from the non-dynamic sectors, and also by the expansion of the dynamic sectors.[16]

It is possible to advance the hypothesis that the evolution of the bioeconomy is also determined by the development of its industrial sector, as was the case in the fossil fuel-based economy, and that the rate of growth of the industrial sector in the bioeconomy determines the level of innovation. Growing demand for goods from the industrial sector of the bioeconomy will depend on product innovations – completely new products or environmentally friendly and sustainable substitute products (cf. Table 5.1).

The role of the state is key for the implementation of innovation of quality. Innovations, especially product innovations, require the creation of new markets for them, which cannot exist without its involvement.[17] When thinking about growth in terms of investment and new products, disinvestment has to be considered to be the starting point. When wanting to move capital and labour into new areas, they first have to be released from old, low-productivity sectors or areas generating too many externalities. Every disinvestment is a loss and represents a threat to someone. In such a situation, it is not protection and subsidies which are necessary, but instead policies to speed up the process of disinvestment and exclude inefficient companies from the market. Often countries find it difficult to get out of low-productivity industries and products even if economic and ecological analyses would seem to call for it.[18]

Figure 5.7 show how the level of innovation measured in terms of productivity and demand for industrial products of the bioeconomy will be determined by employment in industrial production in the bioeconomy in its growth phase.

With constant growth in demand for production of the industrial sector, the employment equation is not opposed to the productivity equation. Growth in the ratio of change in demand to change in productivity will cause growth in employment.

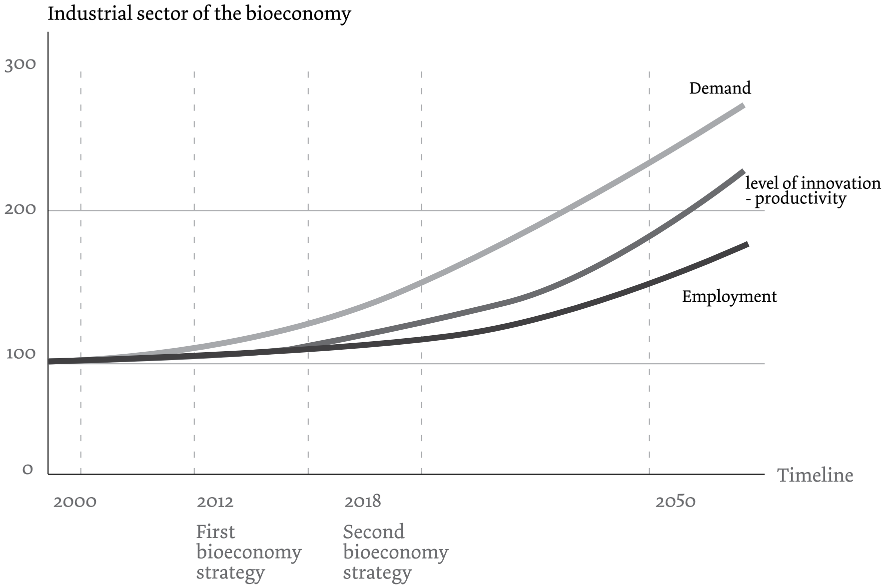

Figure 5.7 Change in the level of innovation measured in terms of productivity, demand and employment in the industrial sector of the bioeconomy.

Source: Own elaboration.

As long as the growing rate of demand from the industrial sector of the bioeconomy is faster than the rate of growth in productivity in industry, employment will grow with it. Growth in demand in the bioeconomy for industrial production in the first period of its evolution will depend on the conditions of creation of innovation. These, above all, include the possibility of introducing new goods, products not known to date, which are characterised by better or other properties, which necessitates the creation of a new market.[19] Growth in demand for industrial production in the bioeconomy will also be strongly dependent on social innovations, and especially innovations in the institutional and political spheres. Change in the structure of demand for industrial goods from products of traditional industry to products of industry of the bioeconomy is key here, however. Analysing change in demand for industrial goods manufactured in the bioeconomy and productivity, where both variables are determined by the level of product and technological innovation, and the ratio of changes in them, a great deal of convergence can be seen in the direction of these changes for the agricultural sector. This points to a strong connection/interdependence of these sectors in processes of development/evolution of the bioeconomy (Figure 5.8).

The level of employment in the bioeconomy will grow. In the bioeconomy, raw materials are produced, in contrast to fossil fuel raw materials, which are extracted. The extraction of raw materials is limited by physical resources available, and innovations (only of a technical and technological nature, because there can be no product innovations) measured in terms of productivity in the extractive industry only have a very slight impact. If raw materials are produced

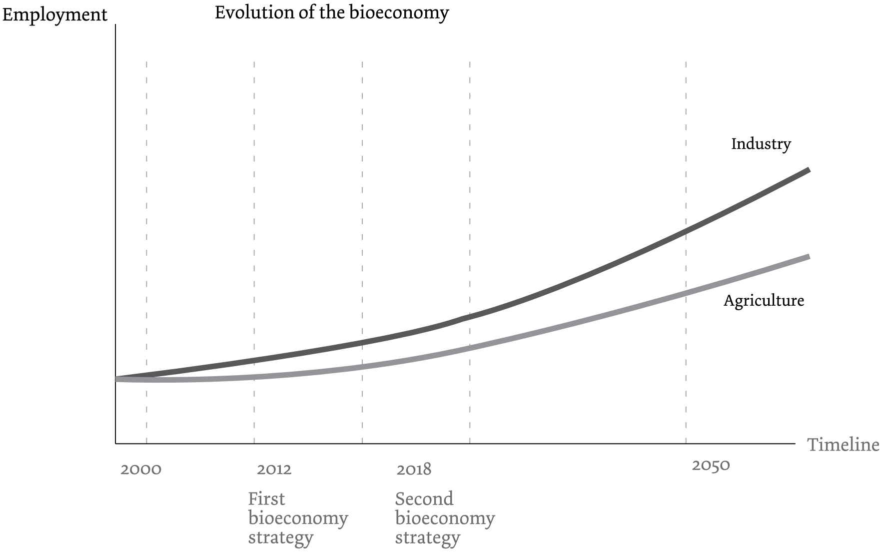

Figure 5.8 Evolution of the bioeconomy.

Source: Own elaboration.

and not extracted, then innovations will determine their market competitiveness, as production itself creates potential for innovation.

For the evolution of the bioeconomy, growth in the level of innovation in the agricultural sector will be key, as it leads to an increase in the competitiveness of biomass, which translates as an increase in demand for it in the industrial sector. This directly determines growth in demand for products of the industrial sector, which become more competitive in terms of price (and quality, thanks to product innovations), which translates as an increase in demand for production of the agricultural sector. In other words, the share of the agricultural sectors grows together with growth in the share of overall production of the bioeconomy of the industrial sector.

The rate of evolution of the bioeconomy will depend on growth in demand for production of the industrial sector and growth in productivity, as well as productivity in the agricultural sector. The main determinants of these factors are the level and quality of innovation. In addition, taking into consideration that, in processes of evolution of the bioeconomy, the rate of development of the industrial sector and of the agricultural sector is positively correlated with and determined by the level of innovation, their interaction creates possibilities for innovation. Development of the bioeconomy is based on the capacity for innovation, while, at the same time, creating the space for it and driving innovation.

5.4 From the top to the base of the biomass pyramid: Selected examples of innovations in primary production and bio-based energy

A closer examination of innovations and innovative phenomena involved in the creation of the bioeconomy, ranging from the level of primary production, biotechnology and innovative forms of recovery and processing, as well as examples of bio-based materials (discussed in further detail in Chapter 10) to technologies related with closing the material circulation cycle (discussed in further detail in Chapter 11), would probably be a task requiring a separate monograph of its own. For this reason, this chapter takes a selective approach to this topic, referring above all to primary production and selected aspects of industrial use of biomass.

According to Food and Agriculture Organization (FAO) simulations, in 2050, the population of the Earth will be 9.1 billion people, whose needs in terms of access to food will require growth in food production of as much as 70%. The conventional approach to agriculture, based on synthetic fertilisation of plants and regular, preventive spraying, increases the externalities and the true costs of primary production.[20] Emissions associated with pre- and post-production activities in the global food system are estimated to be 21–37% of total net anthropogenic GHG emissions.[21] The environmental externalities associated with food production alone are:

- air, water and soil pollution
- greenhouse gas emissions

- excessive use of renewable resources
- depletion of soil fertility and resources
- use of scarce materials
- consumption of water,

which contribute to climate change, have significant health effects, and lead to the depletion of abiotic and biotic resources including ecosystem services and biodiversity.[22] This is why there is no future for ‘agribusiness as usual’. Supporting organic farming, permaculture and regenerative agriculture on the one hand and solutions from the fields of IT, the Internet of Things (IoT) and robotics (Figure 5.9) in primary production on the other are tools for sustainable agriculture.

Precision Agriculture is a management strategy that gathers, processes and analyzes temporal, spatial and individual plant and animal data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production.[23]

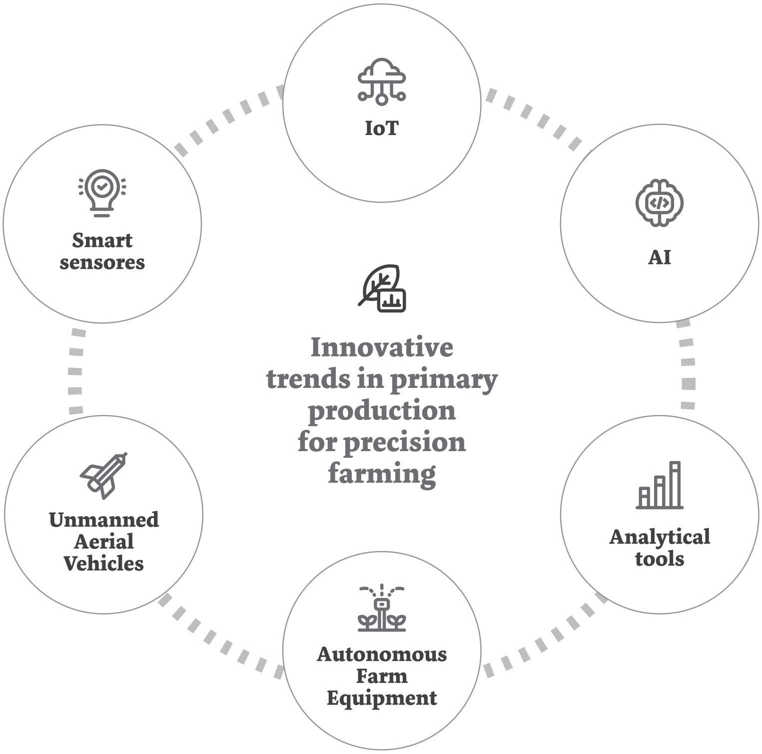

Figure 5.9 Innovative trends in primary production.

Source: Own elaboration.

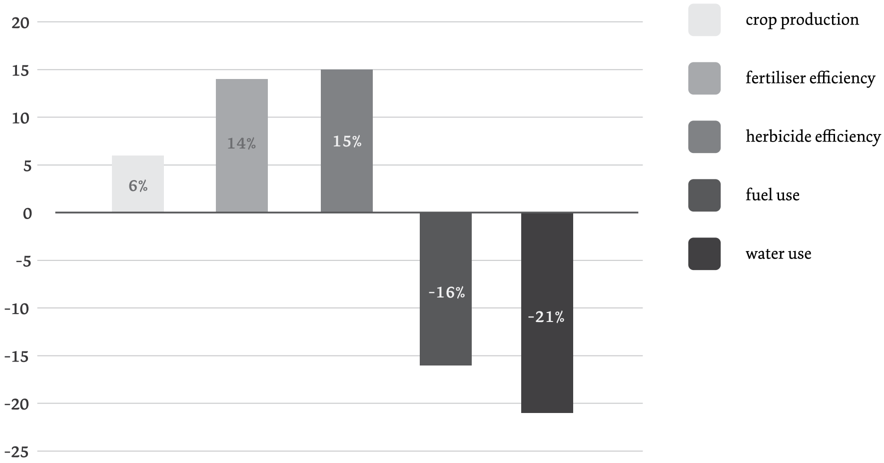

Figure 5.10 Impact of precision agriculture on the efficiency and costs of farms in the USA.

Source: Own elaboration based on data from: Association of Equipment Manufacturers, Julius Baer, https://www.juliusbaer.com/en/insights/feeding-the-world/farm-of-the-future-how-to-produce-more-with-less/

From the perspective of primary production, innovations should lead to improvement in the sustainability of ecosystems, their reconstruction and conservation, support for biodiversity, and the elimination or minimisation of the environmental footprint, and, due to connections with rural and coastal areas, support regional development and efficiency and competitiveness of production. Studies conducted in North America have been able to observe the partial achievement of the goals mentioned above in the USA (Figure 5.10).

Key areas of innovation impacting the development of precision agriculture are shown in Figure 5.9. Their significance is described in greater detail below.

- **Sensors**: Sensor systems are widely used in primary production, collecting data on the condition of plants and their environment. Monitoring of greenhouses and vertical, hydroponic or aeroponic cultivation systems allows measurement of temperature, light, moisture and condition of the soil, which also has an impact on the quality of cultivation, and, for example, allows water loss to be kept to a minimum.[24] In livestock farming, sensors allow the spread of infections to be prevented and problems with individual animals to be detected.
- **IoT**: Use of sensors is connected with the use of the Internet of Things. Sensors remotely activate smart systems for irrigation, temperature control, fertilisation, etc. or transmit information to a person responsible for taking decisions concerning these processes, who can then also react to the problem remotely.

- The application of **AI** in agriculture combines computer imaging, Natural Language Processing, and machine learning. AI is used, above all, for data management and analysis. AI algorithms can predict weather patterns and propose, or by using IoT trigger, appropriate activities; they can also optimise consumption of water and of plant protection and nutrition products; as well as detect diseases, outbreaks of parasitic organisms, etc.
- These activities can be carried out using **Unmanned Aerial Vehicles**, or drones and **Autonomous Farm Equipment**. The activities of these devices is often related to use of the Global Positioning System (GPS). Its use covers the mapping of terrain and computer-aided data collection, such as, for example, keeping inventories of types of crops, field boundaries, and the location of irrigation systems. The use of GPS allows agricultural machines to work more autonomously, fuel consumption to be reduced and efficiency of fertiliser application to be improved.[25] Geographic information systems (GIS) focus on the analysis of spatial data. They consist of geospatial monitoring equipment and software for analysis of the information gathered. GIS systems provide support for the preparation of appropriate crop plans and the management of cropland resources, which may lead to an increase in crop productivity while reducing the costs of production.[26] A GPS system does not, however, recognise phases of crop development, which is why it is necessary to call upon the support of optical or mechanical contact systems, referred to as Local Positioning Systems (LPS). They collect data about the level of development, weed infestation, plant diseases and nutrient deficiencies. Variable Rate Application (VRA) devices for precision sowing, fertilisation and plant protection, as well as autonomous vehicles, are used at the next stage. The activity of VRA machines is based on maps prepared in advance of content of nutrients in the soil, soil types or yields.

Hugo is an agricultural robot created to meet needs to limit the use of chemicals on agricultural crops, especially in the area of fungicide use. Currently available methods of combating fungal diseases in field crops require 2–3 protection treatments using the same dose of fungicides applied to the entire surface of the field, regardless of the individual degree of plant infection. The proposed technology allows early crop canopy diagnostics and rapid, individual, dedicated stimulation of plant defence mechanisms protecting against pathogens. The Hugo technology has been implemented by the start-up Hugo Green Solutions sp. z o. o. The patented, unmanned vehicle platform with a modular construction is integrated with post-emergence plant irradiation technology. This technological solution makes use of achievements in precise agriculture and teledetection. The robot is equipped with a work module, the main element of which is a Cartesian manipulator – working on the XYZ axes, precisely stimulating better crop growth. In addition, it also has a roving control module. The spectral camera allows the state of health of plants to be identified in real time. Based on image analysis, it conducts an individual assessment and precisely stimulates plants to strengthen defence mechanisms to protect against pathogens. Use of the Hugo robot on field crops can effectively limit use of chemicals on the farm. The robot is the result of pre-deployment studies carried out at the University of Agriculture in Kraków (Figure 5.11).

Figure 5.11 Hugo, a field robot.

Source: Own elaboration.

In addition to using the above-mentioned systems, this mapping may be based on the use of drones and multi-spectral techniques making use of green, red, red edge and near-infrared wavelength bands, which allows for the development of the following indicators and information:

1 NDVI (Normalised Difference Vegetation Index) – used to determine the state of development and condition of vegetation. It is based on the contrast between the strongest reflectance in the near-infrared band and absorption in the red band.
2 LAI (Leaf Area Index) – is the ratio between leaf surface area and land surface area. Allows the degree of use of light by the plant to be determined. Establishing the optimum value of the index makes it possible to achieve higher yields.
3 NDRE (Normalised Difference Red Edge) – determines the health of plants based on chlorophyll content. NDRE is lowest for soil; unhealthy plants have slightly higher values. Healthy plants attain the highest values. In addition, it also shows variability in demand for fertilisers, nitrogen adsorption, stress and vigour in plants.

4 CHI (Crop Health Index) – shows the healthiness of crops based on measured chlorophyll content.
5 Identification of pests, diseases and weeds,
6 Soil fertility and nutrient deficiencies[27]

The action of all of the above-mentioned tools is reinforced if proper **analytic tools (data analysis software)** are also applied, providing information about the need to take specific actions, not only in order to avoid excessive use of chemicals and water consumption, but also with regard to the conservation and maintenance of equipment in appropriate condition and the forecasting of yields.

Precision farming systems allow all stages of primary production to be carried out from soil preparation, sowing and yield monitoring to crop protection and pollination.

Certain elements of precision farming (e.g. sensors and environmental monitoring) are used in specialist cultivation systems, some examples of which are provided in Table 5.3.

Increasing changes in the natural environment, such as changes in climate, water relations, soil quality, and the presence of pathogens, are forcing people to look to a more innovative approach to agriculture. Though precision farming provides an answer to these problems to a certain extent, an innovative approach may also involve the modification of plant characteristics, thanks to specialist breeding and genetic engineering; as well as activities, which can hardly be called innovations, because they consist of a return to sources which have been forgotten. They do, however, demonstrate changes in ways of thinking, so they can be considered a kind of social innovation. Reaching for the traditional knowledge of local communities is becoming increasingly popular in South America. One example is the cultivation of açaí berries. Historically, they were consumed by indigenous peoples, who over the centuries have developed effective methods of selecting them and increasing productivity in agroforestry systems. Today, the açaí berry links farmers in the Amazonian systems with global markets. Techniques of production, as well as of harvesting and processing, have been optimised. The income of berry producers is significantly higher than the earnings of employees in other agricultural activities (which are the main factors in deforestation), despite the fact that the berry is of lower value than beef and tropical hardwood.[34] Another example can be found in the area of livestock farming. The routine administration of antibiotics in livestock farming has now become the norm, leading to a rise in the antibiotic resistance of pathogens, environmental pollution as a result of them entering the environment, and a negative impact on human health. Solutions based on past knowledge are thus becoming increasingly common. For example, in pig farming, Chinese medicinal herbs reduce the frequency of diarrhoea in weanling piglets by increasing the respiratory burst and Salmonella-killing ability of polymorphonuclear neutrophil (PMN) cells.[35] European traditional herb mixtures[36] used as an antibiotic substitute have also been shown to be effective in protecting herds, whilst at the same time also helping to improve the

Table 5.3 Cultivation systems

Cultivation system	*Description*
Hydroponics	Consists of growing plants in water instead of in soil. Allows plants to be grown more quickly and crop quality to be controlled, and also increases nutrient content in plants.[28]
Recirculating aquaculture	Though it has existed for 65 years, it is still considered to be an innovation. It consists of the cultivation of fish and/or shellfish in land-based, indoor tanks in a controlled environment where filtration is applied to purify water through removing metabolic wastes. This process involves mechanical and/or biological filtration, sterilisation, and oxygenation, allowing over 90% of water to be reused and nutrients to be recycled.[29]
Integrated multi-trophic aquaculture	Based on raising species from different trophic levels in proximity to one another. In this system, organic and inorganic wastes of one cultured species are recycled to serve as nutritional inputs for other species. The key benefits of integrated multi-trophic aquaculture include product diversification and faster production cycles. This process improves productivity and profitability of the farm and reduces the environmental cost of aquaculture.[30]
Aquaponics	Combines the benefits of hydroponics and aquaculture. Less water is used and crops are cultivated without the use of fertilisers. Aquaponics is based on metabolic waste produced by fish. This waste is used to feed plants. This method envisages the cultivation of plants with a deep root system and requires the presence of filtration systems enabling plants to make use of the nutrient-rich waste and purify it to remove undesirable substances. Aquaponics allows plants to be grown faster than in a traditional system.[31]
Aeroponics	Soilless method of plant cultivation, not requiring any substrate. Plant roots are kept in growing chambers, which are suspended in the air. As a result, the roots are not exposed to the light. The growing chambers are equipped with misting systems, which spray a solution containing nutrients onto the roots. The advantage of this method is the high absorption of nutrients through the roots, meaning that nutrients are not wasted. Aeroponics is suitable for the cultivation of plants indoors, and its high efficiency is assisted by the adaptation of parameters, such as: concentration of oxygen and carbon dioxide, humidity and light intensity, and the temperature of nutrients.[32]
Vertical farming	System of cultivation, generally used indoors, with mixed lighting systems and systems for the control of fertigation and other environmental parameters. This helps to reduce the negative impact of agriculture on the environment. It has huge potential, which can be seen in locations where energy production is sustainable, ecosystems are fragile, and water and land resources are limited. This solution has certain disadvantages associated with the maintenance high standards of hygiene and increasing the turnover of disposable materials, which has a negative impact on the environment.[33]

Source: Own elaboration.

condition of the animals and meat quality.[37] These are specific examples, but it is now common to see knowledge about the importance of crop rotation and combining species in companion planting being put to use in agriculture. Companion planting is when groups of plants with specific characteristics are grown together in the same space, supporting each other as they grow. The most well-known example of this are the "Three sisters" – maize, beans and squash. The maize acts as a support on which the bean plants can climb. The beans fix nitrogen in the soil. The squash grown around the beans and maize, protecting them against weeds.

An important field in the context of innovation in the bioeconomy is industrial biotechnology. According to Aguilar,[38] it is a key enabling technology in accelerating the transition to a green, low-carbon and resource-efficient economy with the potential to impact on a large number of industrial sectors and social activities. He considers that industrial biotechnology processes are crucial for replacing fossil resources by renewable ones and therefore can contribute to mitigating climate change. The development of industrial biotechnology (for more about biotechnology, see Chapter 10) is accelerating the development of new solutions which place less of a burden on the natural environment. Industrial biotechnology also has an impact by decreasing energy consumption and cleaner energy production (Figure 5.12).

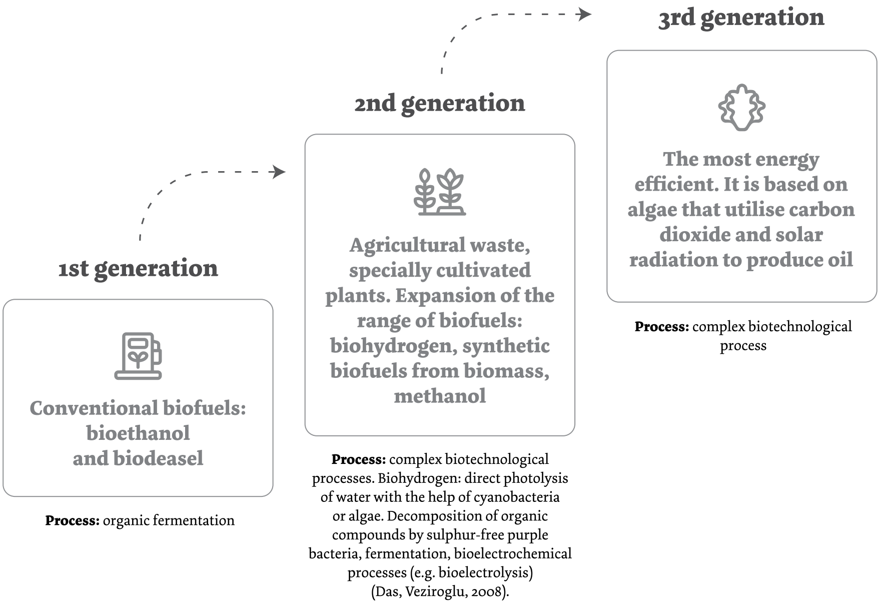

Figure 5.12 Development of biofuels in the context of biotechnological processes.

Source: Own elaboration.

Obtaining energy from biomass is a controversial area, especially when a traditional approach is taken to understanding this problem, which is associated, above all, with burning wood. In fact, this is an example of a situation in which the use of forest biomass has a negative impact on ecosystems, biodiversity and the capacity of forests to mitigate the effects of climate change. In the EU, from 2004 to 2019, the quantity of wood harvested for energy production increased by nearly 25%. In Poland, from 2004 to 2020, annual consumption of wood biomass rose by ca. 70%, and the total quantity of wood biomass used in bioenergy increased nearly 140-fold, from 35,000 cubic metres to 4.9 million cubic metres. The quantity of wood biomass used for energy production and coming from domestic resources increased by 47.6%. In parallel to this described phenomena, import of wood from abroad is also intensifying.[39] The cultivation of plants for energy raw materials is highly controversial, especially when it comes to the use of high-quality agricultural land that could be used to cultivate plants of higher value or when such cultivation has taken the place of valuable natural ecosystems. It can even be said that such an approach runs contradictory to the meaning of the bioeconomy, understood according to the definition as 'sustainable production and processing of bioresources'. Nevertheless, energy can and should be produced from biological resources, subject to the hierarchy of values presented in Figure 6.1. Demand for energy is going to grow in future and modern bioenergy is now the largest source of renewable energy globally, accounting for 55% of renewable energy and over 6% of global energy supply (https://www.iea.org/energy-system/renewables/bioenergy). There is a broad range of methods of obtaining energy that have already been implemented (cf. Table 5.4).

Table 5.4 Method of obtaining energy from biomass

Method of obtaining energy from biomass	*Description*
Biomass combustion	Burning biomass is the most important form of renewable energy ever used. Modern biomass combustion can reduce life cycle GHG emissions by up to 90% compared to the respective fossil alternatives. Newly built plants focus on innovative technologies like chemical looping combustion, which features higher CO_2 concentrations in the flue gas and thereby reduces sequestration costs. Bioenergy with carbon capture and storage (BECCS) is also a promising technology.
Gasification	Gasification is the thermo-chemical conversion of solid biomass or residues into product gas. Product gas can be either used for direct heat and power generation or upgraded into green gases or liquid products. The product spectrum includes hydrogen, synthetic natural gas (SNG), liquid transportation fuels, kerosene, and chemicals. Gasification is thus significantly more versatile than direct combustion.

(*Continued*)

Table 5.4 (Continued)

Method of obtaining energy from biomass	*Description*
Direct thermochemical liquefaction (DTL)	DTL covers two main technologies: solvent liquefaction and pyrolysis. Both can use a range of resources and wastes from biomass. The products of these processes are bio-crudes (from solvent liquefaction) or bio-oils (from pyrolysis). Bio-oil and bio-crude are energy-dense liquids, obtained from biomass, that are easier to transport and handle. Fast pyrolysis bio-oil is used for heat production in boilers. Bio-oil and bio-crude can be upgraded for use as low-carbon-intensity biofuels for transportation, and also as chemicals and other valuable products. Solvent liquefaction can be described as the pyrolysis of biomass in the presence of a pressurised solvent. Pyrolysis is a biomass densification step (e.g., torrefaction) to increase energy density.
Biogas production for heat, electricity, and transport	Produced from biodegradable wastes (e.g., organic fraction from municipal solid waste), industrial by-products/wastes (e.g., food and beverage industry), agricultural by-products, and wastewater. Biogas can be produced from purposely grown biomass feedstock, for example, maize or so-called cover crops, which allow an additional crop to be harvested on an agricultural cultivation area. Biogas production is a process of anaerobic fermentation. As the organic matter (proteins, carbohydrates, fats) degrades, it is converted to intermediates (hydrogen, volatile fatty acids, alcohols, etc.) and finally to biogas, consisting mainly of methane and carbon dioxide, together with small amounts of hydrogen, hydrogen sulphide, ammonia, and water. Biogas can be used for heating and power production. Energy producers can upgrade it to biomethane. After the anaerobic fermentation process, a residue called digestate remains: consisting of undegradable biomass, nutrients, and water. These digestates (either liquid or solid) are suitable for use as fertilisers in a circular economy approach.
Transport biofuels	Biodiesel, bioethanol, and hydrotreated vegetable oils (HVO) are widely used. Feedstocks for the production of transport biofuels include oil-seed crops, sugar and starch crops, lignocellulosic agricultural and forestry residues, and even micro- and macroalgae. Mechanical, chemical, thermochemical, and biochemical processes are applied to convert these feedstocks into transport biofuels. It is possible to deploy synthesis technologies for the production of transport biofuels, using renewable hydrogen. Such fuels are called e-fuels or power-to-x fuels.
Biorefining	Biorefining is the processing of biomass feedstocks into industrial products (fibre, protein, and chemical products) and bioenergy. Basing the production of such products on biomasses instead of fossil resources contributes to achieving a more circular economy.

Source: Own elaboration based on IEA Bioenergy, Bioenergy Review 2023. How bioenergy contributes to a sustainable future, https://www.ieabioenergyreview.org/

The above solutions are already quite widely used. The involvement of bacteria is a prerequisite for fermentation processes when producing energy fuels. There are also great hopes for the use of other living organisms – such as fungi and algae. Fungi possess unique capabilities in producing power, fuel, and electricity through metabolic processes. Certain species, such as *Trametes versicolor*, *Ganoderma lucidum*, *Galactomyces reessii*, *Aspergillus spp.*, *Kluyveromyce marxianus* and *Hansenula anomala*, have been reported to generate electricity at 1,200 mW/m^2, 207 mW/m^2, 1,163 mW/m^2, 438 mW/m^2, 850,000 mW/m^2 and 2,900 mW/m^2,[40] respectively. Fungi provide a unique approach to harnessing bioenergy from biodegradable waste materials while actively contributing to environmental remediation. They operate through a combination of microbial and electrochemical processes. Currently, their use as a real alternative is running up against challenges such as scalability, cost-effectiveness and technological optimisation.[41] Algae appear to be a slightly more promising source of energy. They already play a role in numerous commercial applications: ranging from the production of dietary supplements to wastewater remediation. The oil produced by algae can be used directly, after esterification, to make biodiesel or be refined, for example, to make diesel and jet fuel. Carbohydrates from algae can be fermented to produce additional biofuels – ethanol and butanol, while algal biomass can be used to produce pyrolysis oil or for combined heat and power production. One example of use of the energy potential of algae is the BIQ House in Hamburg, built over a decade ago, which uses bionic energy. The building is covered in panels containing live algae. They process solar energy in a similar way to photovoltaic panels. When the colony grows, the algae are collected in a special chamber, and are then fermented to produce biogas. In addition to energy, they also produce oxygen. The BIQ House does not require any additional external supply of power.

Similar areas of innovation – primary production and energy supply – do not represent the full innovative potential of the bioeconomy, but are more like a clasp binding different sectors of the bioeconomy together, which are at extreme poles of biomass value pyramid – namely, food and energy; and, at the same time, are products of first necessity for modern civilisation. Innovative bio-based materials, bio-based chemicals, drugs and supplements, and biotechnological progress as a whole, are perhaps the sectors showing the spectacular progress in terms of innovative processes today.

5.5 Innovation as the basis for EU economic strategy

The ambitions of the European Green Deal and the achievement of Sustainable Development Goals require the implementation of an innovative approach to achieve climate neutrality, protect biodiversity and, at the same time, guarantee a high standard of living for citizens. The constitution of a mature bioeconomy in European countries is related to their innovative potential, the readiness of businesses to take risks, the readiness of governments to create safe transformation conditions for those businesses and the readiness of consumers to

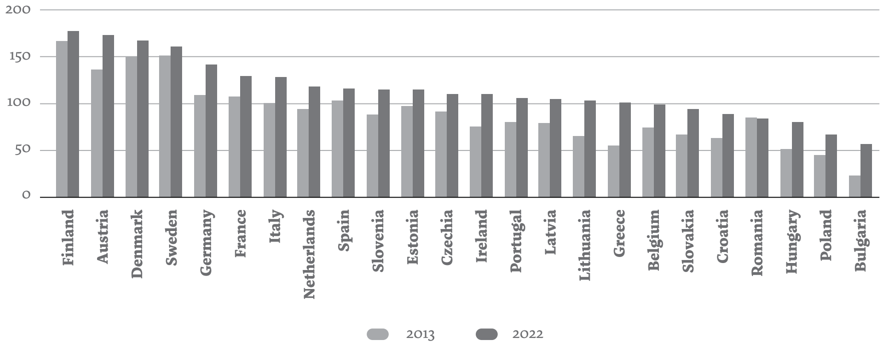

Figure 5.13 Eco-Innovation Index in EU countries 2013 vs 2022.

Source: Own elaboration based on data from https://green-business.ec.europa.eu/eco-innovation_en.

accept production and consumption according to the circular (bio)economy model. Reluctance to innovate and the inability to implement innovations starting from the product level, via the process level, and finally at the behavioural level, may perpetuate the (bio)economic stratification of Europe, with certain countries remaining producers of biomass while others make use of this raw material and generate added value from it. Though there is no index of innovation in the bioeconomy, it can be assumed that innovations in the area of the circular bioeconomy form part of what is understood more broadly as eco-innovation,[42] which has been measured since 2010. The difference between the level of innovation in various European countries is shown in Figure 5.13.

From Figure 5.13 it can be seen that there is a deep divergence between a group of innovator countries and a group of 'conservative' countries. Finland, Austria, Denmark, Sweden, Germany, France, Italy and the Netherlands are far ahead of Bulgaria, Poland, Hungary, Romania, Croatia and Slovakia. A low level of innovation is associated with countries which have been caught in the middle-income trap, are characterised by low industrial diversification and non-poor working conditions. The transition from an economy based on raw materials and cheap labour to an economy based on high productivity and innovation is a major challenge for these countries. There may be many reasons at the origin of this state of affairs, The first of these can be attributed to historical conditions – six of the least innovative countries are former satellite countries of the Soviet Union. This is not, however, an argument which satisfactorily explains the whole picture, notably in the cases of the Czech Republic and Slovenia, which have jumped ahead of the other countries with which they share the same historical experience. One important reason explaining this may be the unfavourable institutional environment, bureaucracy, the lack of any satisfactory solutions for start-ups and investors, but also agricultural conditions, such as the significant fragmentation of farms, and lastly cultural issues, such as a limited tendency to take risks in business, low tolerance for mistakes and failures, and a culture of education, which does not encourage creative and critical thinking. The largest seller of food in 2022 was France, with income of 97.1 billion euros, followed by Germany (76.2 billion euros), Italy (71.5 billion euros), Spain (63 billion euros) and Poland (39.5 billion euros). Notably, Poland is in second place behind Romania when it comes to the number of people employed in agriculture,[43] which is testimony to a rather low level of efficiency of production. A huge opportunity is opening up for traditional agricultural countries in Europe, which will not be made use of, if their (bio)economy is closed to innovation. Countries such as Poland or Romania may then fall victim to the resource curse.

We are faced with the need to transform the rules of production so that its effects do not contribute to overshooting the planetary boundaries that guarantee the survival of ecosystems. Historically, the turning points which have set the economy on a new course have been related to inventions and advances in knowledge – over two centuries of capitalism these inventions were associated with the move towards mass production, the use of fossil fuels as a source of energy and to drive that mass production, as well as the development of the steel industry and railways, the initial explosion in and subsequent flourishing of the era of the petrochemical and automotive industries, and finally discoveries in the field of IT. It is possible to speculate that we now find ourselves faced with a next stage in the evolution of the economic system, which is not, however, the effect of spontaneous creative processes, but rather is a necessity imposed by changes in methods of production (and consumption) in order to guarantee the biological conditions for the existence for future generations. As in the periods that have gone before, the condition for progress is innovation – not only in the area of products and the processes by which they are created, but also in social attitudes. Adopting the paradigm of the sustainable, circular (bio)economy requires us to step outside of the framework of conventional ways of thinking about raw materials and the production process. A propensity to innovate may prove to be key to making use of the potential of the bioeconomy. Shifting the focal point from the exploitation of non-renewable resources to the production of renewable raw materials means a change in the balance of global affairs, where countries specialising in the production of biomass have the chance to improve their position on the international stage or position themselves as producers of raw materials.

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12 Where Q – production.

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6 Chosen problems of the commodity science in bioeconomy

Robert Witkowicz, Sławomir Pietrzyk, Dorota Gala-Czekaj and Francois Lategan

6.1 Introduction

Commodity science studies and assesses products and the factors which have an impact on their quality and utility value. Areas of interest in this field cover the whole product life cycle from the design stage, through product manufacturing, distribution, trade and use to end-of-life, which, in the context of the circular bioeconomy, means putting organic substances back into the cycle of matter or their possible transformation into energy, in accordance with the "cradle to cradle" principle. In the area of the bioeconomy, the following products are/will be the subject of interest in commodity science:

- Primary biomass production: goods from agriculture, forestry, aquaculture and fisheries.
- Residues (raw material) from the production of the goods from agriculture, forestry, aquaculture and fisheries.
- Bio-based materials and biochemicals.
- Packaging.
- Conventional and advanced biofuels.
- Bio-based building materials and goods.

The principle in the area of the circular bioeconomy is eco-design. The European Environment Agency defines eco-design as: *The integration of environmental aspects into the product development process, by balancing ecological and economic requirements. Eco-design considers environmental aspects at all stages of the product development process, striving for products which make the lowest possible environmental impact throughout the product life cycle.*[1]

The basic goal of commodity science is to guarantee the proper quality of products, guaranteed by norms, regulations or standards. Product quality is usually analysed from the point of view of the following parameters:

- technical – functions and physico-chemical properties of the product (e.g. composition, weight, structure),
- functional and ergonomic – e.g. functionality, safety, ease of use,

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- aesthetic,
- economic – e.g. price, cost of production, transport,
- ecological – presenting the impact of the product on the natural environment and the consumer's mental and physical condition.

This final aspect is especially important in the context of products containing organic coal, which, by definition, should facilitate the closure of the cycle of organic matter. It should be emphasised that not all bio-based products are biodegradable;[2] and the non-sustainable production of biomass may pose a threat not only to the environment (discussed in further detail in Chapter 8), but, as a result, to society too (discussed in further detail in Chapter 1).

This chapter places the emphasis on two issues which are important from the perspective of development of the bioeconomy: the potential of biomass and its component elements; and the problem of the quality of the products obtained in the content of standardisation and certification.

6.2 Biomass and its components

The current challenges associated with the growing world population, the rapid exhaustion of resources, the increasing expansion of the population and its pressure on the environment, as well as climate change, pose a threat to the stability of ecosystems. Over the next 30 years, the population is projected to increase by 20%, reaching over 9 billion by 2050. If there is no change in food-related behaviours, such an increase in the world's population will lead to an increase in demand for food of about 60%.[3] Nutritional education is, of course, a necessary action that can reduce the negative environmental effects of food production, especially in relation to meat production, but a task of key importance for the bioeconomy is ensuring food security and the production of high-quality food for the future. However, the economic efficiency of the bioeconomy is to be achieved through full use of the potential of biomass. This means that biomass processing should create products with as much added value as possible, according to the value pyramid (Figure 6.1).

Biomass consists of all renewable products and raw materials generated in agriculture, forestry, aquaculture and waste management. It can be solid, liquid or gas substances of organic origin (microbes, plants, fungi, animals). Biomass can be categorised according to various criteria (Table 6.1).

In simple terms, the process of the biomass creation starts with the first component of the trophic chain: the population of autotrophs, that is, organisms with the ability to produce organic compounds from inorganic ones, using mainly the energy of solar radiation (photoautotrophs) but also the energy of chemical reactions (chemoautotrophs). These organisms form the basis of the ecological pyramid that characterises the abundance, productivity and biomass of each trophic level. The amount of organic matter produced by these producers can be referred to as primary production. The main biological process that determines the production of biomass is photosynthesis. Within one year,

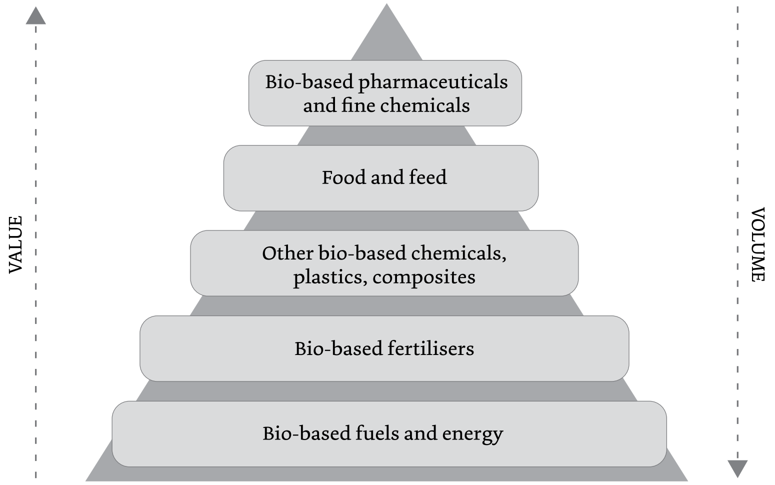

Figure 6.1 Biomass value pyramid.

Source: Own elaboration based on Bos et al.[4]

Table 6.1 Categories of biomass

Categorisation criteria	*Types of biomass*	*Characteristics*
State of aggregation	Gas	
	Liquid	
	Solid	
Origin	'Yellow'	Plant origin, straw, shavings, husks, etc.
	'Green'	Plant origin leaves, grass, clover, etc.
	'Red'	Remains of animal production
	'Blue'	Fish, crustaceans, algae and all organic matter from the seas and oceans
	'Brown'	Organic fraction of sewage
	'Orange'	Organic household waste
	'Grey'	By-products from food processing
	'Purple'	New biomass: fungi, bacteria, microorganisms, arthropods
Energy resources biomass generations	First generation	Edible biomass
	Second generation	Non-edible biomass residues
	Third generation	Algae
Degree of processing	Primary production	For example, crops and other organic raw materials
	Processing of the first degree	Processed within spontaneous, natural processes. For example, compost, sludge, etc.
	Biotechnological processing	Processed by biotechnological processes into materials with new properties, e.g. bioethanol, biocomposites, biopolymers, etc.

Source: Own elaboration.

photosynthesis[5] allows 10^{10} tons of carbon to accumulate in the form of biomass, which corresponds to the accumulation of about 4.2×10^{17} kJ energy.[6] The energy stored in the biomass of phytocenoses is a source of energy for heterotrophic consumer organisms (phytophages – herbivores). This results in significantly less secondary production (secondary biomass) because this is characterised by energy losses associated with the efficiency of energy storage in heterotrophic organisms. To close the energy cycle, reducers (destructors) are still needed to break down biomass to inorganic compounds, which again become available as biomass resources to producers.

A commodity science assessment of products of the bioeconomy may be based on numerous different criteria, ranging from determination of the environmental footprint of the product and of the process by which it is created, to its functional characteristics, composition and properties. For the purposes of this chapter, considerations relating to the quality of biomass will be based on its chemical composition, which is common to products obtained in this area of economic activity.

6.2.1 Proteins

Proteins are a component occurring in all biomass. They are linear polymers consisting of about 20 different α-L-amino acids linked by trans-peptide bonds. Amino acids, from a nutritional point of view, are divided into two groups: exo- and endo-genic amino acids. The most important aspect is the biomass content of essential amino acids, i.e. those that the human body cannot synthesise itself (isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, valine and histidine). Complete proteins are those of animal origin, while plant biomass, is a source of incomplete ones. In addition to their nutritional value, proteins have other functions such as structural and functional properties. The functional properties of proteins are often due to their enzymatic and regulatory nature. The influence of the physico-chemical properties of proteins on the external appearance, texture and rheological properties of foods and raw materials subjected to technological processing also cannot be underestimated.[7]

The need for high-quality protein is only set to grow. At the same time the Food and Agriculture Organization of the United Nations.[8] reports that in 2022, an annual global total of 1.05 billion tons of food are wasted, having passed its expiry date. This loss amounts to one-fifth of the food produced. This represents a huge amount of biomass from which a number of valuable and rare chemical components can potentially be recovered and re-used. Bio-based intermediates such as proteins and mono-acids can be produced from the protein-rich wastes of bio-based materials. Good examples are animal biomass wastes, such as hog hair, bird feathers, fish flesh and entrails, chicken slaughter waste, whey and shrimp shells. By-products are also obtained from plant biomass (e.g., bean dregs, silk fibron, rice bran, de-oiled soybean meal, sugarcane and ginger bagasse, peanut shell waste, corn stalks), aquatic biomass (e.g. *Laminaria, Arum*). In order to reduce the world's protein deficit, there are calls to extract protein from the leaves of plants e.g., *Glycine, Glyricida* and *Leucaena*. Another proposal is to introduce insect protein into the diet. There are currently 1,500–2,000 species of insects (e.g., *Melanoplusfemurrubrum, Sphenariumhistrio*, *Melanoplusmexicanus*) consumed worldwide because of the unique, highly digestible protein they contain, with protein content that can reach up to 60–80%.[9]

More effective and efficient protein extraction methods are being developed. Hydrolysis at subcritical and supercritical conditions may provide an efficient process for recovering useful chemicals from biomass wastes and for the disposal of biomass wastes. The effectiveness of this method, compared to others, is determined by a number of chemical and physical factors.[10] Also nitrogenous compounds can extracted from unusable food and the side products from the entire value chain. One promising process for such transformation is sustainable microbial fermentation for production of high-value bio-based intermediates. Amongst these products, proteins and enzymes make up a significant group. Using appropriate microbial species (e.g., *Aspergillus* sp., *Bacillus* sp., *Lactobacillus* sp. or *Saccharomyces* sp.), it is possible to obtain simple cell proteins and a variety of enzymes e.g., protease, *b*-glucosidase, pullulanase, xylanase, which can be used in building new substances for use in subsequent parts of the value chain. The enzymes obtained in this way can be used in various biocatalytic reactions, on both a laboratory and an industrial scale. Of particular interest are enzymes immobilised on natural materials (e.g., *Aplysina archeri*, chitin, lignin) or nanomaterials. Such systems are used to remove or biodegrade many toxic substances from the environment, including antibiotics. Examples of raw materials used in this process include brewery waste, wheat bran, soybean or cottonseed meal, orange or pomegranate peel, corncob, and rice husk. The high economic potential of food waste prompts the need to obtain from them high-value bioproducts like biofuels, biopolymers, nanocomposites, enzymes and bioactive molecules. Unfortunately, one serious limitation is the chemical heterogeneity of food waste.[11] This prompts the "expensive" thought of the need for waste collection based on chemical composition. Only such chemically homogeneous biomass will optimise the operational efficiency of biorefineries.

A numerous group of bio-based intermediates are plant proteins (gluten and soy protein) and animal proteins (collagen, casein, keratin, silk – fibroin, sericin). They provide excellent raw material for the production of packaging films with different properties, as well as fabrics. A casing for sausage products made from collagen has been particularly successful. Collagen peptide-based raw material has inherited properties such as antimicrobial efficiency, the property of accelerating the healing of wounds, and other sustainable characteristics. Collagen can be extracted from fish waste and purified to be used in cosmetics, medical research, sports clothing, and nutrition, etc. Fibres with added collagen peptide were recently regenerated to enhance cellulosic fibres, which are known to provide a skin-friendly texture. Fish skin (salmon, trout) can be turned into leather. Vegan alternatives are being actively sought to replace animal leather with bio-based alternatives such as plant fibres or fungal *mycelium* fibres in the face of global climate change challenges. Cactus leather is a promising bio-based alternative product, as it can simulate many of the functions of animal leather.[12] High-quality fabrics can also be obtained from soybean protein, zein protein, casein protein after adding a biodegradable synthetic polymer.[13] Due to the essentially protein-based nature of blood, medical research, too, has contributed to the identification of its alternative uses. Initially, the idea of polymerising blood molecules may facilitate the development of new strategies for *in vivo* cell engineering with synthetic macromolecules. The resulting polymer is beginning to find non-medical applications.[14]

6.2.2 Carbohydrates

Globally, the most common organic chemical compounds of natural origin are carbohydrates. They occur in all organisms, but are produced only by those that contain chlorophyll or bacteriochlorophyll in their cells. In plants, the basic assimilation organs are leaves, whose cells contain chloroplasts. The process of photosynthesis is the only one which uses the light energy from the sun to perform these highly important biochemical transformations in the plant. Photosynthesis provides a natural process to maintain appropriate levels of oxygen in the atmosphere by sequestering carbon and increasing the pool of organic matter. This process is extremely important for closing the carbon cycle, which is essential in the circular economy.

Due to the complexity of their structure, carbohydrates can be divided into monosaccharides and complex saccharides (oligosaccharides and polysaccharides). The term carbohydrates also includes derivatives of the previously mentioned groups, including polyhydric alcohols. The huge diversity in the structure of carbohydrate molecules causes them to perform a number of functions in plant organisms (e.g., as energy source, reserve substance, building element like cell walls and mechanical tissues, and osmotic and receptor function) and influences the taste, texture, nutritional and energy value, and rheological properties of raw materials and finished products. Both mono- and polysaccharides can be obtained from plant biomass.

Until recently, the transformation of monosaccharides consisted of their transformation into derivative compounds by microorganisms. Two fermentation processes were mainly used for this purpose: 1. alcoholic (aerobic process) and 2. lactic (anaerobic process). The main products of these transformations are ethyl alcohol and lactic acid, respectively. The first of these processes is carried out mainly by *Saccharomyces*, and the second by *Lactobacillus*. The use of ethyl alcohol, due to its low toxicity, is well known (e.g., engine fuel, antiseptic and disinfecting effect, solvent, and as an ingredient of cleaning, preservative, and cosmetic products). Lactic acid is used in cosmetics and, as a product of live bacterial cultures, it is treated as a probiotic. The last dozen or so years have been a period of intensive work on lactic acid, allowing it to be given the status of a “green polymer” used in the production of biodegradable packaging. It is used to produce both flexible packaging (e.g., foils, labels) and rigid packaging (e.g., cups, trays, bottles). Methods of microbiological modification of carbohydrates have also been used to transform starch into its more valuable forms e.g., a specific chemical reaction is catalysed by *Bacillus* enzymes, converting starch into cyclodextrins. These compounds are widely used in the pharmaceutical, cosmetics and food processing industries for microencapsulation.[15]

The depletion of natural resources, including wood biomass, has significantly increased the role of monosaccharides obtained from waste, including wood processing (e.g., in the production of paper). The monosaccharides produced as a waste from the production process of paper can be converted into compounds with greater utility value that are used in the food, chemical or pharmaceutical industries in appropriately designed enzymatic bioreactors. Xylose, for example, can be effectively converted into xylonic acid and glucose into gluconic acid. These substances can productively be used as resources for other bio-based processes. A good example is the use of xylonic acid (a five-carbon sugar acid) in popular industrial applications, including the food, pharmaceutical and construction industries. New methods of obtaining raw materials in the form of monosaccharides (five- and six-carbon molecules) allow for a significant reduction in the negative impact of previously used methods on the environment.[16]

Hydrolysis at subcritical and supercritical conditions (water temperature conditions exceeding boiling point used under high pressure conditions) may provide an efficient process for recovering and extracting reduced sugars from lignocellulosic biomass wastes. It is worth emphasising that such cellulose hydrolysis does not require the use of any mineral acids. One of the most important natural materials commonly found in nature is cellulose. This polysaccharide is composed of β-D-glucopyranose molecules connected by β (1-4)-glycosidic bonds. The main sources of cellulose are wood, cotton, linen, hemp, but also algae. Obtaining cellulose requires a delignification process, which has a heavy impact on the environment. Therefore, several studies were undertaken to reduce the environmental hazard of the delignification methods used. This also included research into innovative methods such as 1. enzymatic delignification, 2. hot water delignification and 3. green solvents in delignification. Cellulose is also synthesised by the bacteria *Acetobacter xylinum*. The obtained material is characterised by greater purity and crystallinity, and the fibres are longer and stronger. This makes it suitable for use in specialised procedures in the medical, electronics and paper industries. Nanocellulose (synthetic product produced industrially) also has similar properties. These celluloses are used, for example, to produce microtubes, dressings, nanocomposites, aerogels, and transparent paper. Cellulose with worse technical parameters (and therefore more cost-effective) is used to produce cellulose fibres and films for the packaging, paper, food and medical industries.[17] Hemicelluloses are polysaccharides, other than cellulose, present in the cell walls of higher plants, which may include, for example, xylans, mannans and galactans. This biopolymer has a low calorific value and stimulates the development of the microbiome. In industry, hemicellulose is used as an additive to polymer mixtures (cellulose substitute). Pectins are interesting polysaccharides that can be obtained from land plant biomass. Significant amounts of pectins are to be found in post-production fruit and vegetable pomace. Pectins are heteropolysaccharides, whose main structure consists of D-galacturonic acid esterified with methanol to a varying degree. The main property of pectins used in industry is their capacity to form gels, which results in them being used as a stabiliser, emulsifier or gelling agent mainly in the pharmaceutical, food and cosmetics industries. Pectins also find applications as a material to adsorb metal ions and as a filler in composites to control/maintain humidity in the environment, and are used as a component of various coatings, including those with antibacterial properties (e.g. medical and food packaging). A group of valuable heteropolysaccharides in the form of alginates, agar, carrageenans and furcelleran are obtained on an industrial scale from various types of algae and as a metabolite of micro-organisms, e.g. xanthan.[18]

Inulin is also a natural heteropolysaccharide popularly used in the food industry. Inulin is basically a linear fructan composed of fructosyl units [β (2-1) bond] and usually contains one terminal glucose moiety [α (1-2 bond] per molecule. The hexoses from which inulin is composed are the most common monosaccharides. Bonds occurring between the units give inulin a prebiotic character, because the human enzyme system does not hydrolyse them.[19] Chemical hydrolysis of bonds allows the transformation of the obtained hexoses into 5-hydroxymethylfurfural (HMF), which is then oxidised to 2,5-furandicarboxylic acid (FDCA). FDCA is easily transformed into compounds with high added value (e.g., macrocyclic ligands, polyesters, polyamides). Of course, hexoses from other biomass sources can be transformed into HMF, e.g., 1. edible biomass, 2. non-edible biomass, 3. food and feed wastes biomasses.[20]

The second most common polysaccharide on Earth is chitin, composed of β -D-glucosamine molecules connected by a 1-4 glycosidic bond. Chitin occurs mainly in the exo-skeleton of insects and arthropods and the cell walls of fungi and bacteria. Currently, the chitosan used for industrial applications is mainly derived from crustaceans, especially crab, prawns and shrimp shells. The exoskeletons of these crustaceans are readily available as waste derived from the food-processing industry. The most important chitin derivative with the greatest potential for use is chitosan. In the food industry, it is used as a supplement to aid obesity control. It has hypocholesterolaemic properties and is an excellent material for producing biodegradable packaging. Chitosan has been employed as natural preservatives for meat and other food products against fungal spoilage. Chitosan is used as a preservative for fruits and vegetables and helps in preventing loss of nutritional value. Chitosan is a non-toxic substance and is used to obtain drugs with specific properties, e.g., those that are released in appropriate sections of the digestive tract and have anti-microbial and anti-cancer properties. It accelerates wound healing and is useful as a bio-scaffold for tissue engineering, especially for skin and bone wounds. It is used as an ingredient in cosmetics, especially those intended for skin and hair care, since it forms a protective layer after use. It is used in the textile, paper, and agricultural industries (antiviral agent, additive in fertilisers, plant regulator and agro-products preservative). In environmental protection, it is used to purify sewage water and drinking water.[21]

Starch, along with cellulose, is a renewable polysaccharide widely used in many industries. It is obtained mainly from the biomass of plants rich in this polymer (cereals and potatoes). An additional source of this polysaccharide may be post-production waste generated in the agri-food industry, especially from the production of processed food. Starch is composed of α -D-glucose molecules connected by α glycosidic bonds (α 1-4 glycosidic bonds in amylose; α1-4 and α1-6 glycosidic bonds in amylopectin). This structure allows for complete digestibility of this polymer by humans, but only after preliminary hydrothermal treatment (cooking). In its natural state, starch is insoluble in cold water, but, when heated to a temperature above 70 ˚C, it gelatinises. After cooling to a temperature below 50 ˚C, starch pastes begin to gel. It is mainly to these functional properties that starch owes its use in the food and pharmaceutical industries as a texturising or thickening substance. Native starch often does not have the expected technological properties and is therefore commonly subjected to modification (physical, chemical, enzymatic). In the food and pharmaceutical industries, modified starches are carriers of nutrients which are naturally deficient (e.g., minerals, fatty acids, flavouring substances) or replace lipids, reducing the calorific value of food. In the textile and paper industry, the improved film-forming properties of modified starch is mainly used. The better these properties, the better the yarn fibres are glued together, and the threads have a more durable, thinner, and more flexible membrane. These film-forming properties make the paper more resistant to tearing and bending. This paper is also specially used in the production of banknotes and securities. Modified starches are also used as coagulants and flocculants in the water purification process and slow down the corrosion of metals. As a result of modification, starch may become soluble in cold water, form pastes of the required viscosity or be carriers of specific chemical substances. Starch hydrolysates are used as an addition to cement mixtures to increase the plasticity of concrete. Natural and modified starches, as substances that absorb large amounts of water, are successfully used in children's diapers, as well as in wound dressing materials. Modified starch is used to produce biodegradable packaging or is a component of a composite with other polymers, both synthetic and biodegradable. Ongoing research is being conducted into the use of starch polymers as a material for 3D printing and micro-encapsulation. Another form of starch is oxidative starch, which is characterised by a significantly increased ability to bind metal ions, which allows for its use as a component of detergents, paints, mineral fertilisers and animal feed. In the case of creams, their addition not only increases the viscosity of the creams but can also give these creams bacteriostatic properties (Cu(II)). Oxidised starches are used in the mining and drilling industries to bind with and remove metal ions from drilling fluids.[22]

6.2.3 Lipids

Lipids, like proteins and carbohydrates, are a component of every living cell. They form a large group of natural organic compounds whose chemical distinctiveness results from the presence of various functional groups. Another term commonly used to describe this group of compounds is "fats". Fats, apart from the main group of triacylglycerols, also contain small amounts of other lipids (accompanying substances). Generally, "fats" are understood in this way (vegetable, animal) if the content of triacylglycerols exceeds 95%. Therefore, the quality of the fat being tested will mainly be determined by the variable elements contained in the triacylglycerol structure, i.e., fatty acids and other lipids. Within the large group of fatty acids, there is a subgroup that is extremely important for humans and is called essential fatty acids (EFA). The necessity of these EFAs results from the body's inability to synthesise these acids, where the multiple bonds are located in specific places in the molecule (n-3 and n-6).

Free fatty acids, especially EFAs, can be obtained from waste biomass by converting the components contained in this biomass into lipids inside microbial organisms. The bio-based intermediates obtained in this way are called single cell oils (SCOs). Single cell oils are oils derived from oleaginous fungi, yeasts, bacteria, microscopic algae and protists. Oleaginous microorganisms can accumulate significant amounts of lipids (~20–80% of their body weight) inside their bodies. Oil obtained from the biomass of organisms is non-toxic and biodegradable and is therefore suitable for, and used as, consumer and feed oil and to produce carbon materials (polymerisation, cracking) or biofuels. The latter applications (biofuels and the production of biomaterials) are limited by the availability of appropriate biomass (e.g., waste from the production of olive oil) for this type of development. Biomass with a high lipid content can also be subjected to anaerobic fermentation to obtain biogas.[23]

Another way to transform biomass into valuable bio-based intermediates is to use insects. Amongst the many insect species currently bred on an industrial scale, several meet the criteria for safe inclusion in the animal feed production cycle (e.g., *Hermetia illucens*, *Musca domestica*, *Tenebro molitor*, *Alphitobius diaperinus*). The result is that the protein obtained in this way is acceptable for feeding in aquaculture. Both lipids and proteins in the larvae body may reach 30–50% of body weight respectively. The efficiency of biomass transformation by *M. domestica* maggots reaches 50–60% of biomass (which contains about 55% organic carbon).

Another possible source of valuable bio-based intermediate products, including fatty acids, is biomass from microalgae (e.g., *Nannochloropsis* sp., *Isochrysis* sp., *Phaeodactylum* sp.). Due to the unique composition of the obtained oils, it is mainly used in the food (e.g., nutraceuticals) and cosmetics industries. Technical uses (e.g., biopolymers) and energy uses (e.g., biogas) are secondary uses due to the cost of obtaining biomass. Algal biomass contains about 80% water, which limits the uses of energy for drying and environmentally safe extraction methods (e.g., solvent extraction, supercritical fluid extraction) and forces the development of new extraction methods e.g., hydrothermal carbonisation, in which ethanol (a renewable and food-grade solvent) is used for extraction. A good example of lipid components with a wide and varied range of uses is biomass from spent coffee grounds.[24]

High-fat waste biomass, both of plant and animal origin, with a lipid content generally not exceeding 40%, poses a significant waste management problem. In addition to solid biomass, an important category of waste in this group is sewage with a high content in organic compounds. These organic compounds can be successfully cleaned microbiologically. Solid biomass (especially of animal origin) approved for further processing is mainly directed to biorefining, similarly to olive- and rapeseed-derived (canola) biomass and waste cooking oil. Waste cooking olive and canola oil can be a source of biodiesel, or it can be disposed of using microorganisms (e.g., *Aspergillus* sp. *Penicillium* sp.). In fat fermentation performed by these microorganisms, the free fatty acids liberated after lipase-catalysed hydrolysis of the triacylglycerols will be incorporated inside the microbial cells or fungal mycelia and will either be dissimilated to meet the growth needs of the microorganisms or become a substrate for intracellular biotransformation. This means that waste cooking oil can be subjected to microbiological fermentation (anaerobic digestion).[25]

Another valuable source of phenols, lipids and organic acids is the phytotoxic (for soils) residue from olive oil extraction (pomace or solid residue waste). This biomass occurs in huge amounts because olive trees are grown over an area of more than 10 million hectares worldwide. The chemical composition of the waste allows it to be considered an alternative source of e.g., natural tannins obtained from mimosa, quebracho species, chestnut, etc., and many other bio-ingredients. This biomass, like others, can also be converted into energy, which should be considered to be the definitive solution. This transformation includes pyrolysis, combustion, gasification, and fermentation. The pyrolysis process converts biomass into gas, bio-oil, and biochar. Bio-oil as a bio-based intermediate can be used as an additive to asphalt or, e.g., to produce hydrogen.[26]

6.2.4 Minerals and ash

Minerals are elements that, in addition to water, carbon, hydrogen and nitrogen, are part of every plant and animal organism. Their presence and content depend primarily on the organism's membership of the plant or animal kingdom. Generally, minerals are divided into two groups: macro- and microelements. Belonging to a given group results from the concentration of a given element in the body. Minerals are not only building materials, but also play an active part in biochemical processes occurring in living organisms.

Ash is the residue left after complete combustion of an organic substance at high temperatures. Therefore, the main components of ash are mineral substances, including heavy metals. In the bioeconomy, combustion and pyrolysis of plant and animal biomass and waste biomass (from the agri-food industry) are commonly used processes, which generate a significant amount of available ash. The main elements included in the ash are Ca, Si, Al, Ti, Fe, Mg, Na, K, S, P, and their content and chemical form varies. The chemical composition of biomass is important because the high content of alkaline and chemically aggressive chlorine may cause corrosion of power equipment and the formation of deposits on the heating surfaces of the boiler. The ratio between alkaline compounds (Fe_2O_3, CaO, MgO, Na_2O, K_2O and P_2O_5) and acidic compounds (SiO_2, Al_2O_3 and TiO_2) contained in biomass ash is an indicator characterising not only the suitability of the biomass for combustion, but also determining the possibility of further use of the ash. Generally, ash obtained from burning plant biomass is used in agriculture as a source of scarce minerals and as a carrier of pesticides. However, special attention should be paid to the possible presence of heavy metals in the ash, which limits the possibility of their use. Ash from plant biomass is often introduced into the soil as an ingredient of soil improvement mixtures, and, in so doing, contributes to improving the physical and chemical properties of the soil. The second important industry that uses the ash produced in this way is the construction industry. Research shows that the chemical composition, grain size and reactivity of ash allows it to be used in the production of concrete, cement, and building ceramics. New and innovative practices in energy waste management also include the use of ash as fillers in polymer materials technologies, such as polypropylene, polyvinyl chloride, polyethylene, and polyethylene terephthalate. The sorption properties of ash are also used in the purification of sewage, in the binding of petroleum substances, and in removing pollutants from the air, soil and water. Ash with an appropriate mineral composition can be used as a raw material to produce synthetic zeolites with ion-exchange properties used in electronics, pharmaceuticals, cosmetics and optics. Effective use of ash reduces the negative environmental effects of its storage. The use of this waste as a secondary raw material allows for the implementation of sustainable development goals in the energy and industry sectors.[27]

6.2.5 Other components

Other important components of biomass are vitamins, polyphenols, pigments and alkaloids. The content of these compounds in biomass compared to the basic components is significantly lower, but the source (biomass) allows them to be obtained on an industrial scale. These compounds are mainly obtained by extraction with the appropriate solvents, from raw materials of both plant and animal origin.

Vitamins are a chemically diverse group of compounds necessary in trace amounts to ensure the proper growth and development of organisms. For animals, the majority of them are exogenous compounds, which means they must be sourced from outside of the organism. For this reason, vitamins are used as additives in food (including dietary supplements), feed, cosmetics and pharmaceuticals. The primary sources of vitamins in nature are plant biomass, and then microorganisms. In addition to being manufactured by chemical synthesis, vitamins are also produced using biotechnological methods (e.g. E, C, K2, B2, B12, B7).

Polyphenols are secondary plant metabolites and constitute an important group of natural compounds with primarily antioxidant properties. There are about 8000 of these compounds known to us today, to be found accumulated mainly in leaves, vascular tissues, bark, seed coverings and unripe fruit. They are obtained directly from plant raw material and from post-production waste from the agri-food industry (mainly pomace). The unique properties of these compounds (antioxidant, bacteriostatic, anticarcinogenic, antiatherosclerotic) make them suitable for use mainly in the pharmaceutical, food and cosmetics industries. One unconventional use of tannins was an attempt to produce foam inserts for sports shoes (to obtain inserts with better mechanical properties).

Pigments are chemicals that absorb electromagnetic radiation of a wavelength of between approximately 400 and 700 nm. Pigments are isolated from concentrated extracts obtained from plant or animal raw materials. The most frequently isolated plant pigments include chlorophylls, anthocyanins, carotenoids, xanthophylls and betalains, and animal pigments include haem pigments, melanins and cochineal. Natural pigments are used, amongst other things, for the colouring of foods, drugs, cosmetics, textiles, paper, and leather goods.

Alkaloids are compounds which occur not only in the plant world, but in animals too (insects, amphibians, beetles). In plants, they are most often found in leaves, seed and fruit, though they can also be found in the bark, roots, bulbs and flowers. Alkaloids have a strong physiological effect on the bodies of both humans and animals. There are currently over 12,000 known compounds of this type. Some of the most well-known alkaloids are: atropine, brucine, quinine, codeine, caffeine, cocaine, mescaline, morphine, nicotine, reserpine, strychnine and theobromine. Due to their specific effect on the human body, alkaloids isolated from plant biomass or produced using microorganisms are mainly used in the pharmaceutical and cosmetics industries. Originally obtained from plant biomass, compounds of this group were previously unrecognised for their use to poison arrows. Curare (a mix of various related alkaloids) is obtained from different morphological parts of species such as *Strychnos toxifera*, *S. guianensis*, *Chondrodendron tomentosum*, *Sciadotenia toxifera*, and *Mostuea*. *Strychnos toxifera* is also a source of antiarin, strychnine and strophanthin. Curare is also used in anaesthesiology. Uncontrolled extraction of plant raw materials containing alkaloids and other valuable chemical substances leads to a threat to stability of species. One of the reasons for this is the use of parts of these plants as herbal medicines (e.g. *Aconitum chasmanthum*, *A. heterophyllum* and *A. violaceum*). Many species of plants considered to be poisonous also contain cardiac glycosides. Parts of the *Acokanthera* (ouabain), oleander (*Nerium oleander*), milkweed (*Asclepias*) and *Strophanthus* (strophanthin) plants contain these compounds. In the right concentrations, they are transformed from poisons into valuable heart medications. Bark of the *Cinchona* and *Pausinystalia johimbe* plants is also a valuable raw material. From the former, we obtain quinine, which is both an important drug and a well-known flavouring additive contained in carbonated drinks e.g. tonic). The bark of *Pausinystalia johimbe* contains the alkaloid yohimbine, which was mainly used as an aphrodisiac before the advent of sildenafil (Viagra).

Alkaloids, as valuable components of biomass occurring in low concentrations, are difficult to obtain in the required quantities. The biotechnology sector is starting to play a helpful role by genetically modifying microorganisms that acquire the capability to produce these compounds. The transgenic microorganisms most frequently used to produce alkaloids include *Escherichia coli* and *Saccharomyces cerevisiae* both individually and concomitantly. The many types of alkaloids obtained also include terpenoids and phenols important for medicine. Alkaloids are also obtained from glands on the skin of salamanders (samandarin, samanine) and frogs (batrachotoxin).[28]

Selected, potential possible uses of biomass in different branches of the bioeconomy are presented in the previous chapter. Of course, research continues to conducted into innovative ways of making better/fuller use of biomass. However, to ensure that processes are carried out in a way which meets our expectations/the principles of the bioeconomy, a range of standards and procedures have been introduced to monitor these processes and their effects, including in economic terms.

6.3 Standardisation, certification and labelling in the bioeconomy

6.3.1 Examples of standardisation in the bioeconomy

Standardisation creates a framework and guidelines for processes and products, usually developed by consensus among stakeholders, which all interested parties in an industry or organisation undertake to follow. This guarantees that all processes related to the creation of a product or the provision of a service are carried out in accordance with established guidelines and that the final product is of consistent quality and is comparable to other equivalent products of the same class. Standardisation activities are carried out by state agencies, interest groups and independent international organisations. Examples of international standardisation organisations are ISO (the International Organization for Standardization) and CEN (the European Committee for Standardization). In the context of the bioeconomy, standardisation, certification and labelling are concerned above all with:

- biomass,
- food and feed products,
- forest products and agricultural commodities,

- biofuels and biomaterials,
- heat and power,
- "other" bioproducts (bioproducts that are not biomass, forest products, agricultural commodities, biofuels and biomaterials),
- end-of-life of a commercialised bioproduct.[29]

It is worthwhile starting by taking a closer look at the relationship between standardisation, certification and labelling. The basic principle is voluntary participation in the system. The general scheme is based on the relationship: standard > certificate > label. An exception to this scheme are mandatory labels related to information about safety or compliance with selected standards: e.g. no testing on animals, energy class, etc. ISO frameworks are based on three types of standards:

- Type I (ISO 14024): voluntary, multiple-criteria-based ecolabelling programme assessed by an independent third party, which takes product life cycle considerations into account. The organisation awarding the certificate may be a government organisation or a private non-commercial entity (EU Ecolabel, Blue Angel).
- Type II (ISO 140210): Self-declaration by the producer regarding environmental activities or product characteristics.
- Type III (ISO/TR 14025): Self-declaration by the producer containing objective, quantitative data. An example of this is the Environmental Product Declaration – EPD, a document which presents information on the impact of a given building material on the environment throughout its whole life cycle.

From the point of view of the bioeconomy, it is important that the standards implemented are based on the principles and criteria for a sustainable bioeconomy proposed by the FAO (Table 6.2). The circular nature of the bioeconomy demands a thorough understanding of the infrastructure that supports recycling and remanufacturing, whilst supporting positive benefits, harnessing opportunities, reducing negative impacts on society and the environment while fostering growth. The bioeconomy, therefore, establishes new frameworks for external collaboration and changes the way organisations interact with their networks to ensure their sustainability. The principles and criteria presented are also necessary to ensure that the usefulness, adequacy and effectiveness of the standards are maintained on an ongoing basis.

The principles therefore primarily focused on the traditional areas of sustainable development – environmental, social, economic and cooperation. They should be reflected in standards created for the bioeconomy. As the bioeconomy is a component part of so many sectors, it is not possible to name and discuss all the individual standards here. Some examples of standards in the area of the ISO international classification are presented in Table 6.3).

Table 6.2 Principles and criteria for a sustainable bioeconomy

Principles	*Criteria*
Sustainable bioeconomy development should support food security and nutrition at all levels	• Food security and nutrition are supported. • Sustainable intensification of biomass production is promoted. • Adequate land rights and rights to other natural resources are guaranteed. • Food safety, disease prevention and human health is ensured.
Sustainable bioeconomy should ensure that natural resources are conserved, protected and enhanced	• Biodiversity conservation is ensured. • Climate change mitigation and adaptation are pursued. • Water quality and quantity are maintained, and, as much as possible, enhanced. • The degradation of land, soil, forests and marine environments is prevented, stopped or reversed.
Sustainable bioeconomy should support competitive and inclusive economic growth	• Economic development is fostered. • Inclusive economic growth is strengthened. • Resilience of the rural and urban economy is enhanced.
Sustainable bioeconomy should make communities healthier, more sustainable, and harness social and ecosystem resilience	• The sustainability of urban centres is enhanced. • Resilience of biomass producers, rural communities and ecosystems is developed and/or strengthened.
Sustainable bioeconomy should rely on improved efficiency in the use of resources and biomass	• Resource efficiency, waste prevention and waste re-use along the whole bioeconomy value chain is improved. • Food loss and waste is minimised and, when unavoidable, its biomass is reused or recycled.
Responsible and effective governance mechanisms should underpin sustainable bioeconomy	• Policies, regulations and institutional structures relevant to bioeconomy sectors are adequately harmonised. • Inclusive consultation processes and engagement of all relevant sectors of society are adequate and based on transparent sharing of information. • Appropriate risk assessment and management, monitoring and accountability systems are put in place and implemented.
Sustainable bioeconomy should make good use of existing relevant knowledge and proven sound technologies and good practices, and, where appropriate, promote research and innovations	• Existing knowledge is adequately valued and proven sound technologies are fostered. • Knowledge generation and innovation are promoted.

(*Continued*)

Table 6.2 (Continued)

Principles	*Criteria*
Sustainable bioeconomy should use and promote sustainable trade and market practices	• Local economies are not constrained but rather expanded through the trade of raw and processed biomass, and related technologies.
Sustainable bioeconomy should address societal needs and encourage sustainable consumption	• Consumption patterns of bioeconomy goods match sustainable supply levels of biomass. • Demand-side and supply-side market mechanisms and policy coherence between supply and demand of food and non-food goods are enhanced.
Sustainable bioeconomy should promote cooperation, collaboration and sharing between interested and concerned stakeholders in all relevant domains and at all relevant levels	• Cooperation, collaboration and sharing of resources, skills and technologies are enhanced when and where appropriate.

Source: Own elaboration based on FAO[30], 2021. Aspirational principles and criteria for a sustainable bioeconomy. Rome.

Table 6.3 Bioeconomy-related ISO standards examples

ISO	*Year*	*Title/Description*
14044	2006	Environmental management Life cycle assessment Requirements and guidelines./Standard concerning the methodology for the life cycle assessment (LCA) of products or services.
14040	2006	Environmental management Life cycle assessment Principles and framework./Like the 14044 standard concerns life cycle inventory analysis for products or services.
26000	2010	Guidance on social responsibility./Standard containing guidance on social responsibility. Helps all types of organisations, in both the public and the private sector, wishing to take advantage of the benefits of socially responsible behaviour.
18606	2013	Packaging and the environment Organic recycling./Standard specifies procedures and requirements for packaging that are suitable for organic recycling.
14001	2015	Environmental management systems Requirements with guidance for use./Standard containing requirements concerning the main elements of environmental management: environmental policy, planning, implementation and operation, checking of compliance and corrective action, management review.
13065	2015	Sustainability criteria for bioenergy./Standard specifies principles, criteria and indicators for the bioenergy supply chain to facilitate assessment of environmental, social and economic aspects of sustainability.

(*Continued*)

Table 6.3 (Continued)

ISO	*Year*	*Title/Description*
16620	2015/2019	Plastics – Bio-based content. Part 1: General principles and Part 2: Determination of biobased carbon content./ Specifies the general principles and the calculation methods for determining the amount of biobased content in plastic products and regulates the determination of the bio-based carbon content in plastic products, polymers and additives.
20400	2017	Sustainable procurement. Standard whose purpose is to assist organisations with the implementation of sustainable practices and procurement policies.
14024	2018	Environmental labels and declarations – Type I environmental labelling – Principles and procedures/ISO 14020 series (14020, 14021, 14024, 14025), global eco-labelling principles and procedures
38200	2018	Chain of custody of wood and wood-based products./The ISO standard provides consumers with information about the origin of the wood in the products they buy.
14067	2018	Greenhouse gases Carbon footprint of products Requirements and guidelines for quantification./Standard containing requirements concerning the quantification of GHG emissions at the product level.
17225	2021	Solid biofuels – Fuel specifications and classes/Standard determines the fuel quality classes and specifications of graded firewood.
17088	2021	Plastics – Organic recycling Specifications for compostable plastics./Standard specifies procedures and requirements for plastics, and products made from plastics, that are suitable for recovery through organic recycling.

Source: Own elaboration.

As Gottinger[31] et al. report, in the area of European standards, it is possible to identify nearly 300 bioeconomy-related standards published between 1980 and 2021. The two largest sub-groups of standards are ‘Biofuels’ – 57 standards and ‘Biology. Botany. Zoology’ – 49 standards.

It is worthwhile paying some attention to CEN/TC 411 “Bio-based products” standards group (Table 6.4), which was tasked by European Commission[32] with the development of standards for bio-based products covering aspects including consistent terminology, sampling, bio-based content, the application of and correlation with LCA, sustainability criteria of biomass used, and guidance on the use of existing standards for end-of-life options.

The market for bio-based products is growing thanks in large part to these guidelines. By offering standard reference techniques and specifications that facilitate the verification of claims and certification about the bio-based content, biodegradability or environmental sustainability of various products, they play a significant role in promoting market transparency.

Table 6.4 Characteristics of the standard: CEN/TC 411 – bio-based products

Aspects	*Description*
Terminology.	CEN/TC 411 provides a standard on common terminology (EN 16575) to assist consumers in understanding the characteristics of bio-based products, like biodegradability, sustainability and compostability.
Bio-based content.	The amount of biomass contained in a product should be indicated by, e.g., its bio-based content or bio-based carbon content. It is important to note that environmental impact or sustainability cannot be assessed from the bio-based content of a product. This may be assessed through LCA methods and sustainability criteria.
Standards developed for fossil-based products, applied for bio-based products.	Problematic situations arise when standards/regulations that have been developed for fossil-based products are applied for bio-based products. This creates challenges when expected to "prove" that bio-based materials are equivalent to traditional materials. Standards are important to indicate the additional advantages of bio-based products.
Business-to-Business (B2B) and Business-to-Consumer (B2C) communication.	The term "biomass-based" or "bio-based" refers to the origin of the raw material. The prefix "bio-" refers to different functionalities (biodegradable, biocompatible, etc.) or their origin (origin: plant based and/or produced by biotechnological processes). These are part of a bio-based product and should be communicated to customers, creating the need for two standards, one for the business-to-consumer (B2C) and one for the business-to-business (B2B) communication.
Labelling/certification	The market contains many different and often overlapping certification schemes and certificates, several of them being region- or sector-specific. Businesses operating in different regions are, therefore, required to be certified by these specific schemes (more or less similar certification), thus creating significant costs without adding significant value.
Sustainability criteria/Origin of Biomass/Life Cycle Analysis.	The production of biomass may involve a chain of activities ranging from the growing of feedstock via products to final energy conversion at end of life. Each step along the way may pose different sustainability challenges that require management.

Source: Own elaboration based on: CEN/TC 411, https://standards.iteh.ai/catalog/tc/cen/c98bbdfa-0c42-4d96-86ce-8123d5c2e730/cen-tc-411.

6.3.2 Certification and labelling in the bioeconomy

Standards, certifications, and labelling (SCL) programmes for bioeconomy-related industries have been created with the following goals in mind:

- to provide information about a product's end-of-life possibilities (such as biodegradability, compostability, and disintegration),
- to prove the bio-based content of a product,
- to demonstrate the extent of its sustainability.[33]

Moving onto the discussion of certification and labelling, it is worthwhile starting by emphasising the differences and relationships between these categories. Certifications is usually connected with the awarding of a label. For example, EU-certified organic food production is connected with the 'Green leaf' label. There may, however, be situations in which the awarding of a label does not require certification (cf. Figure 6.2), as in the case of labels providing information about products which are GMO-free, energy-efficient, or not tested on animals, etc. Labelling has the following functions: informative, educational, marketing, image-related, related to corporate social and environmental responsibility, and political. It helps consumers to decide about the shape of the market and the direction in which it is developing. Education of consumers and clear labelling is key for public participation in the implementation of the sustainable strategies for a product.

Product labelling and certification are two different processes, but both aim to provide customers with certainty about the quality, safety or other characteristics of products. Certification is a process whereby an independent organisation assesses a product against certain standards or requirements and officially confirms that it meets these standards. Certifications can cover various aspects such as quality, safety, sustainability, compliance with industry standards, etc. Certification authorises the use of a label that confirms the certified features of the product.

In the area of products of the bioeconomy, there are numerous certificates and labels confirming specific product characteristics. To simplify somewhat, they can be broken down according to the sectors in which they are used.

1 Sustainable agricultural and forestry products,
2 Biomass,
3 Biofuels and biomaterials,
4 Other bio-based products (those not classified as agricultural or forestry products, biomass, biofuels and biomaterials),
5 End-of-life of a commercialised bioproduct, or, in other words, circularity of the product.[34]

Or, by simplifying the breakdown, according to the proposal of the Forum for Biobased Innovations for Public Procurement:[35]

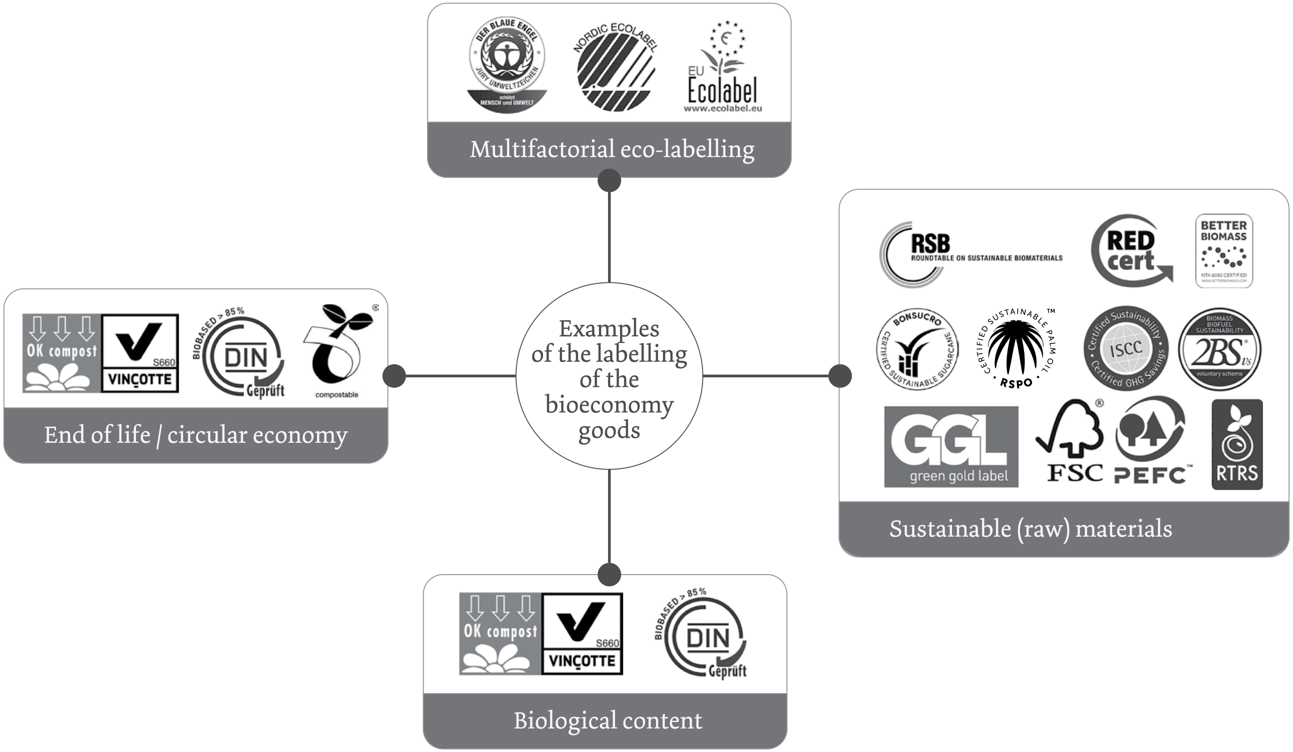

Figure 6.2 Labelling for the bioeconomy.

Source: Own elaboration based on https://www.biobasedconsultancy.com.

1 Multiple-criteria-based labels for bioproducts: on the European market, one possible example of this are the type I three multiple-criteria-based ecolabels compliant with ISO 14024. They are the EU Ecolabel, the Nordic Ecolabel and the Der Blaue Engel label. Products which may receive these labels include oils and lubricants, sanitary products, disposable single-use items for food and office supplies.
2 Labels indicating sustainable raw materials and materials: in response to EU policy on renewable energy, certifying bodies proposed systems for the certification of agricultural biomass, which meet the conditions set out in the EU Renewable Energy Directive (RED) from 2009, such as FSC- or PEFC-certified wood.
3 Labels confirming the content of material or raw material of biological origin.
4 Labels confirming the possibility of closing the product life cycle, confirming its circularity (cf. Figure 6.2).

Of course, Figure 6.2 does not exhaustively cover all topics relating to ecolabelling in the bioeconomy, though it does show the overwhelming predominance of labels implemented for sustainability in the broad sense. Table 6.5 provides a brief presentation of the characteristics of selected labels.

The certification systems presented in Table 6.5 do not exhaustively cover all topics related to the bioeconomy. Food certification is a separate category, in which the key (though not only) quality standard is ISO 22000, the aim of which is to guarantee food safety. There are numerous aspects to food certification, but the method of production is probably key. The numerous certificates in this area, concerning, for example, organic production and integrated

Table 6.5 Characteristics of selected labels related to the bioeconomy goods and services

Name	*Description*	*Link to the ISO*[36] *or other standard*
Multiple-criteria-based labels		
Der Blaue Engel	The Blue Angel certificate is the oldest certificate in the world (dating from 1978), focussed on the process of processing of raw materials and of the production of goods from the point of view of their impact on the natural environment. This certificate is awarded in over 200 product categories, including paper and wood pellets.	ISO 14024
EcoLabel	The European Ecolabel certificate can be obtained by all products and services, except for food, beverages, pharmaceutical products and medical devices.	ISO 14024

(*Continued*)

Table 6.5 (Continued)

Name	*Description*	*Link to the ISO*[36] *or other standard*
Nordic Ecolabel	The Nordic swan is the official sustainability ecolabel for products from the Nordic countries. It was introduced by the Nordic Council of Ministers in 1989. It is a very demanding certificate covering the whole product life cycle from the raw material, through production and consumption to recycling and/or the end of the product life cycle.	ISO 14024
Single-criteria-based labels confirming sustainable sourcing of raw materials and materials		
FSC Wood FSC Mix FSC Recycled	These certificates confirm that the wood used in the production of goods is sourced from FSC-certified forests. FSC is a global certification system and organisation which sets the standards for responsible forest management.	ISO 38200
PEFC	This wood supply chain certificate confirms that the wood used in production is sourced from responsibly managed forests, and the raw material is monitored throughout all production and commercial processes. PEFC is an international organisation promoting sustainable forest management by independent third-party certification. PEFC is not a standardisation body, but rather a system of mutual recognition. The FSC and PEFC account for 98% of the world's Chain of Custody certifications.	ISO 38200
GGL	The Green Gold Label certificate guarantees that biomass products are responsibly sourced. The certificate takes the origin of the biomass (forestry or agriculture) into account, as well as information concerning the supply chain (energy, CO_2 emissions). The certificate covers the whole supply chain: production, processing, transport and ultimately use for bioenergy and bio-based applications.	
Better Biomass	The certificate confirms that biomass is sustainably sourced, taking important environmental and social requirements into consideration.	NTA 8080[37]

(*Continued*)

Table 6.5 (Continued)

Name	*Description*	*Link to the ISO*[36] *or other standard*
REDcert REDcert^2	Certificates confirming the sustainable sourcing of biomass, biofuels and bioliquids (REDcert) and the sustainable sourcing of raw materials used in the food and feed industry, as well as of biomass for use as a material in subsequent stages of the production process (REDcert^2).	
Labels confirming the content of raw material or material of biological origin		
OK bio-based	Certificate confirming content of organic substances based on content of the carbon isotope C14. Certification classes: 20%-–0% bio-based (*OK biobased), 40%–60% bio-based (**OK bio-based), 60%–80% bio-based (***OK bio-based), 80%–100% bio-based (****OK bio-based).	
NEN bio-based	Certificate allows the share of organic material in a product to be assessed. Certification applies to basic materials, intermediate and finished products, as well as to all solid, liquid and gaseous products containing carbon.	EN 16785-1[38]
DIN Geprüft	Certificate confirming a proportion of bio-based carbon within three ranges, but of not less than 20%. Does not apply to medical products, fuels with fossil proportions or products which are poisonous, carcinogenic, mutagenic or harmful for the environment.	CEN/TS 16137[39], ISO 16620
Labels confirming compostability and/or biodegradability		
Compostable	Confirms that a product can be industrially composted. Certifies that at least 90% of the product degrades within 6 months of composting.	EN 13432[40]
OK compost OK compost home	Certificates confirming the suitability of products for composting under industrial and home conditions. The biodegradability period is 6 and 12 months, respectively.	EN 13432
BPI	Certificate ensures that products can be industrially composted. Standard applicable primarily in North America.	
DIN Industrial Compostable DIN Home Compostable	Certificates confirming the compostability of materials, packaging and products under industrial and home conditions.	EN 13432

Source: Own elaboration.

production, as well as a wide range of other certificates at global and local levels, applicable to food in general or created for specific product groups require particular attention. However, discussion of this topic does not fall within the scope of this chapter.

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7 Ecosystem services in the bioeconomy

Jiří Schneider and Agnieszka Józefowska

7.1 Introduction

7.1.1 Ecosystem services – a brief general introduction, definition

Ecosystem services and the bioeconomy are both mutually supportive and mutually beneficial. Bioeconomic procedures and mechanisms can support individual categories of ecosystem services in different ways (from provisioning through to support and regulation) by supporting natural and anthropogenically conditioned cycles of nutrients and trophic chains. On the contrary, by defining changes in the value of ecosystem services, we can express the impacts of different approaches to the management of landscape segments and agricultural products. Ecosystem services can thus be an important tool for developing the effectiveness of bioeconomic approaches and the decision-making process. At the outset, the concept of ecosystem services will be explained and the relationship between ecosystem services and the bioeconomy will be discussed.

Previous chapters have presented definitions of the Bioeconomy from a variety of perspectives: namely, from a socio-economic perspective (e.g. Chapter 1), as well as from the perspectives of biotechnology (Chapter 10) and the environment (Chapter 8). Ecosystem services are defined as all the physical, social, and economic benefits that people can obtain from ecosystems. The term was introduced in the late 1970s to highlight the impacts of biodiversity loss on human well-being and to inform society about it.[1] Gretchen Daily's 1997 study presented the value of ecosystems, and researchers described many ecosystem services such as air and water purification, pollination, climate regulation, and soil fertility. Next, the Millennium Ecosystem Assessment[2] played a key role in putting ecosystem services on the policy agenda. Since its publication, there has been an increased focus on integrating ecosystem services into global sustainability and development agendas. Ecosystem services can link economy, ecology and society to sustainably manage the environment and provide essential benefits to people.[3] Governments, businesses and communities are increasingly recognising the importance of protecting ecosystems for their contribution to human well-being. Furthermore, technological advancements

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are continually refining the methods for measuring, evaluating and conserving these services. Virginijus Sinkevičius, the former European Commissioner for Environment, Oceans and Fisheries, in the recent EU Biodiversity Strategy for 2030, highlighted that "*The latest studies confirm that over half of global GDP is dependent* ***on high-functioning biodiversity and ecosystem services*** *and that globally, one-fifth of countries are at risk of their ecosystems collapsing, compromising food security, clean water and air, and flood protection.*"[4] Taking this definition into consideration, ecosystem services and the bioeconomy complement each other because both branches deal with the sustainable management of the environment for the benefit of society. D'Amato et al. noted that work at the interface between the bioeconomy and ecosystem services "*represents an important space and a fruitful avenue forward*".[5]

The Millennium Ecosystem Assessment classifies ecosystem services into four main categories:

Provisioning (Supply) services encompassing the various products derived from ecosystems. Supply services are easily understood and widely recognised. These services encompass tangible resources directly obtained from the environment, such as food products, fibrous raw materials, and wood. They can be individually examined and evaluated (including in economic terms) within even the smallest ecosystems.

The remaining groups of services are less well-known and often underestimated.

Regulating services involve the alteration of atmospheric composition, the maintenance of stability in significant ecological systems, and the management of geomorphological and pedogenetic processes. Their impact is observable across extensive areas, although localised interactions can disrupt these services. Benefits derived from regulating ecosystem processes encompass carbon sequestration, erosion control, flood prevention, pollination, water purification, and waste management.

Supporting services are essential for generating all other ecosystem services, encompassing tasks such as soil formation and retention, cycling processes, and the provision of habitats.

Cultural services encompass intangible benefits that involve non-material advantages individuals obtain from ecosystems, such as spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences, described as a "potpourri of intangible benefits"[6] or "intangible dimensions".[7]

Ecosystem services are a useful tool in the decision-making process at various levels. They can be understood as a set of indicators, the extent to which they fulfil the effectiveness and effects of economic measures. These indicators can be assessed either individually or collectively. The latter approach proves more advantageous as it allows us to analyse whether a measure targeting the support of one ecosystem service (such as food production) adversely affects other ecosystem services (such as pedogenesis, biodiversity, or landscape retention capacity). Quantifying ecosystem services also facilitates comparisons, for instance, between conventional and organic agriculture or the management of even-aged versus uneven-aged forest stands (see Figure 7.1).

Ecosystem services encompass a multifaceted system characterised by numerous interdisciplinary parameters. For instance, the Common International Classification of Ecosystem Services system alone includes over ninety distinct ecosystem services. Other comprehensive systems include The Economics of Ecosystems and Biodiversity and The Millennium Ecosystem Assessment. As long ago as 1997, Costanza et al. already attempted to estimate the value of ecosystems. They conducted a literature review aiming to evaluate the total global flow value of diverse ecosystems, which also involved a breakdown for marine and terrestrial biomes. The study by Costanza et al. marked one of the initial estimations of the economic value of the environment. They calculated the then annual total global flow value of ecosystem services to be \$33,268 billion.[8]

The determination of ecosystem services lacks a universally fixed methodology, necessitating an analysis of current methodologies or the development of new approaches dedicated to specific ecosystem services. Among the most widely utilised tools are TESSA (Toolkit for Ecosystem Service Site-Based Assessment), InVEST (Integrated Valuation of Ecosystem Services and Trade-offs), and Integrated Ecosystem Services Assessment. The ESVD database (www.esvd.info) provides an overview of ongoing work focused on assessing ecosystem services.

Beyond ecosystem services, the evaluation of the impact of ecosystems on human society also involves acknowledging ecosystem disservices, a facet often addressed in studies such as those by Herd-Hoare & Shackleton[13] and Zabala et al.[14] Ecosystem disservices encompass risks, harms, damages, discomfort, and other adverse effects stemming from the existence of ecosystems. Examples include allergens, diseases, erosion, flood risks, and more. Unlike for ecosystem services, there is no standardised methodology for ecosystem disservices. Their assessment often relies on the perception of stakeholders and society as a whole. They can be expressed by quantifying the costs required for their elimination or by observing decreases in property values or reduced comfort levels, impacted by such disservices. This understanding allows us to describe the characteristics of nearly every ecosystem (Figure 7.2).

To understand the importance of ecosystem services for society and vice versa, it is essential to understand the mechanism by which mutual relations between natural ecosystems and socio-economic systems take place; these are graphically presented in Figure 7.2. Ecosystem service resources (natural capital) bring benefit to human well-being through ecosystem services. The company either manages these resources purposefully or uses them purposefully or arbitrarily. In this way, it affects the ability of ecosystems to produce these benefits.

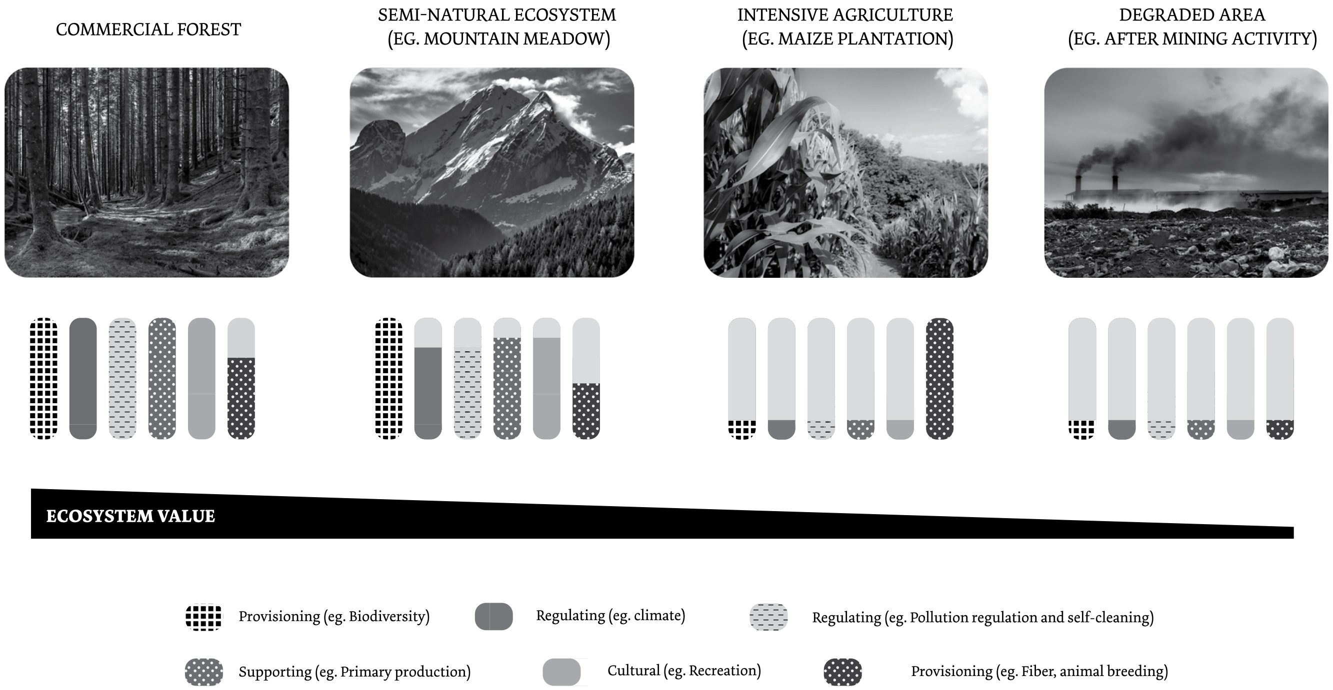

Figure 7.1 Examples of ecosystem services provided by varied ecosystems.

Source: own elaboration based on selected authors.[9,10,11,12]

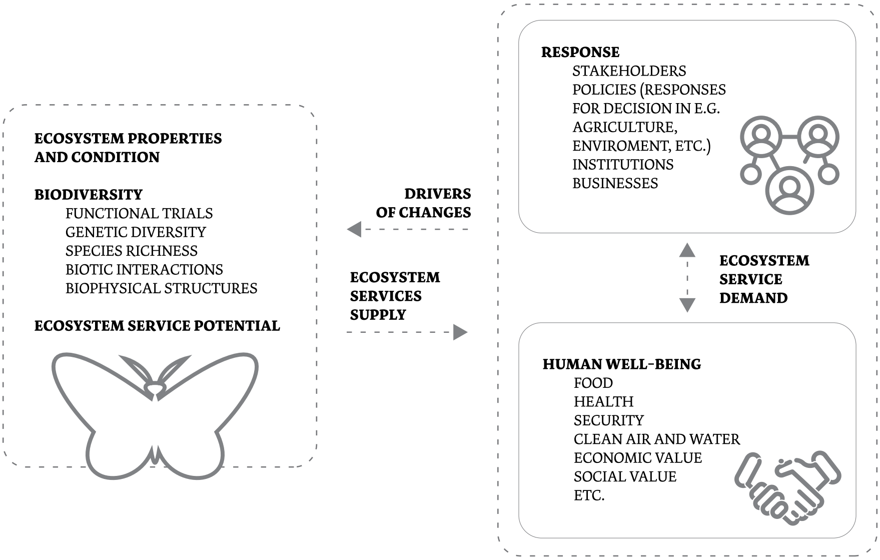

Figure 7.2 The conceptual framework of Action 5 in the EU biodiversity strategy to 2020.

Source: Own elaboration based on Maes et al.[15,16,17]

The value of ecosystem services to society depends not only on awareness and knowledge of ecosystem services but also on the ways in which resources of Ecosystem Services are utilised. The bioeconomy aims for the more efficient (circular) use of products from bioeconomic sectors. The value of ecosystem services to society depends not only on awareness and knowledge of ecosystem services but also on the ways in which ecosystem service resources are utilised. The bioeconomy aims to make more efficient (circular) use of products from bioeconomic sectors. It is not just about the reuse of products – outputs of biological processes (manure or wood chips from forests). It also involves the use of agricultural and forest ecosystems as sources of regulatory and cultural services. For such utilisation of resources, the continuous (permanent) existence of ecosystems, or at least their segments, as part of the landscape matrix or mosaic, is usually crucial.

In addition to social (and consequently financial) value, the immediate quantity of ecosystem services also increases, proportionally with the increasing quantity of their resources and ecosystem processes used directly in the bioeconomy and related sectors. The whole principle of increasing ecosystem production in the bioeconomy is presented in Figure 7.2. Socio-economic systems, including sectors of the bioeconomy, influence the management and utilisation of existing resources and ecosystem services, their quantity and their duration (continuity).

7.1.2 Example of ecosystem services provided by soil biota

Soil is the fundamental production base (not only) of sectors of the bioeconomy. The recycled utilisation of biomass within the sectors of the bioeconomy and, according to its principles, supports its regenerative cycles and pedogenetic processes. These subsequently contribute to sustainable material production and other ecosystem services, including support for soil biota. Soil biodiversity is a suitable indicator for comparing the ecosystem services of linear and circular processes in agricultural production.

Nowadays, no one questions the role and function of soil in the environment. It is relatively easy to translate it into a measurable benefit for humans, e.g. a place for plant growth, a place for buildings, a reservoir of water and nutrients, and many other things. This section will focus on one living element of the soil and show how soil organisms can support sustainable production. A good example of ecosystem services provided by varied ecosystems or group of organisms is shown in Table 7.1. Soil biota offer essential ecosystem services that are vital for sustaining soil health, supporting plant growth, maintaining ecosystem balance, and, ultimately, supporting life on Earth. These services collectively contribute to the functioning and productivity of ecosystems and have significant implications for human well-being. One of the most important ecosystem services – nutrient cycling – involves soil organisms of various sizes, ranging from microbiota responsible for processes such as nitrogen transformations to macrofauna. Earthworms which expedite nutrient cycles and other important processes by incorporating plant residues into the soil (for details, refer to Table 7.1) are an example of this. By discussing a selected example, it can be shown how soil biota is related to biosecurity, biotechnology and bioremediation, which fit into the modern approach to the bioeconomy. For example, it has provided a solution to the current problem of antibiotic resistance – an antibiotic called teixobactin was discovered from a screen of uncultured soil bacteria.[18] Another example is the introduction of biological nitrogen fixation, which can save billions of US dollars and prevent pollution related to nitrogen fertilisation.[19,20]

7.2 Environmental accounting and natural capital as an economic background to the implementation of ecosystem services within the bioeconomy

Environmental accounting and natural capital represent the economic framework of the concept of ecosystem services. Environmental accounting is also one of the economic sectors (including the bioeconomy) for applying ecosystem services in practice. Natural capital represents the earth's stock of natural resources and ecosystems that provide goods and services to people. It includes Ecosystem Services resources such as atmosphere, water, soil, minerals, biodiversity and ecosystems such as forests, grasslands or wetlands. These resources provide essential ecosystem services such as clean air and drinking and domestic water, climate regulation, pollination or recreational opportunities.[29]

Table 7.1 Millennium ecosystem assessment categories of ecosystem services and examples (based on various authors[21,22,23,24,25,26,27,28])

Group	*Category*	*Examples of ecosystem services*	*Example of soil biota involved*
Provisioning services	Food production	Crops, fruit, fish	Entire biota by supporting primary production, e.g. *Fusarium* that has a high protein content
	Raw materials of organic origin	Timber, wool	E.g. *Actinomycetes* sp.
	Other resources of biological origin	Medicine resources, shells, flowers	Antibiotics
	Water supply	Drinking water	Much biota, e.g. adhesion, binding, burrowing restructuring, especially anecic earthworms
Regulating services	Regulation of the air composition	Air-quality maintenance	Much of biota, e.g. adhesion, binding, burrowing, restructuring, plusbacterial/ fungal biodegradatione.g. methane emission (methanogens) absorption (methanotrophs)N oxides (denitrification)
	Regulation of climate	Regulation of the composition of the atmosphere (global scale), temperature and rainfall regulation (local scale)	
	Regulation of extreme events	The timing and magnitude of runoff, flooding etc.	
	Biological regulation	Regulation of the number of pests, pollination and seed dispersal	
	Regulation of soil processes	Soil formation and soil quality	
	Pollution regulation and self-cleaning	Self-purification of water, absorption of dust and gaseous pollutants	
Supporting services	Circulation of elements (nutrient cycling)		E.g. bacteria connected with nitrogen cycle (N-fixation, nitrification etc.)
	Primary production		Cyanobacteria, algae
	Provision of habitat		E.g. soil fauna – earthworms
	Water cycle		Much of biota, e.g. adhesion, binding, burrowing, restructuring
Cultural services	Aesthetic functions		E.g. moles, earthworms, mushrooms,
	Recreation		
	Cultural and artistic resources		
	Spiritual functions		
	Science and education		

Environmental accounting integrates environmental data with an organisation's financial data to provide a comprehensive understanding of a firm's environmental impact. This includes an assessment of natural resources, environmental costs and economic benefits. One of the key components of environmental accounting is the consideration of natural capital. Environmental accounting methods quantify the value of natural capital and enable businesses, governments and organisations to understand the true costs and benefits of their activities. This integration helps make informed decisions that balance economic growth and environmental protection.[30]

Environmental accounting is a suitable tool for assessing the additional benefits of sectors of the bioeconomy and their circular principles compared to linear production processes. As the following text shows, ecosystem services and natural capital represent a methodological link between economic practices and the expression of their environmental benefits. They also enable efficient and generally understandable interpretation and presentation of these benefits for better understanding by the general public.

There are three main mechanisms which allow practical use of ecosystem services in environmental accounting:

1 **Economic expression of the value of ecosystem services** to explain the contribution of natural capital to the economy, human well-being and also the social responsibility of the company.
2 **Informed decision-making –** Knowledge of the value of Ecosystem Services provides environmental accounting with indicators for a comprehensive assessment of the environmental impacts of individual variants of measures and the choice of the most appropriate of variants.
3 **Integration of the impacts of economic systems on natural resources** – The concept of ecosystem services is complex (it includes economic, social and environmental aspects) and therefore enables an understandable expression of mutual benefits and negative impacts between economic activities and the quality of natural resources.

The integration of ecosystem services into economic systems takes place at four levels:

1 **Measuring sustainability**: Ecosystem services helps measure and monitor a company's sustainability performance by quantifying the dynamics of its impact on natural resources and ecosystems.
2 **Decision-making and risk management**: The basic mechanism where the provision of ecosystem services represents a comprehensive system of indicators of the impacts of human activities on the production of a given ecosystem service (see Sections 7.4.2 and 7.4.3 for practical examples). To decide on the option that has the most suitable ratio of impacts on a larger number of ecosystem services (not just on the target ecosystem services). In the same way, the risks of economic activities can be eliminated through early identification of potential negative impacts.

3 **Policy formulation**: Governments use environmental accounting to formulate policies and regulations that promote sustainable development and conservation of natural resources. As a concrete tool, they use the implementation of ecosystem services in the main and partial goals of project calls and financial support.
4 **Investor–stakeholder relations**: Investors and stakeholders are increasingly taking a company's environmental impact into consideration. Environmental accounting provides transparent information through ecosystem services and thus promotes trust and responsibility.

7.3 Economic methods of ecosystem service assessment

There is no one-size-fits-all approach for the economic assessment of ecosystems. On the contrary, ecosystem services can be valued using several methodological procedures, and, in addition, the total value of ecosystems is constructed of a set of different types of values. Thus, a plurality of different approaches and their reasonable balance are needed to assess different aspects of ecosystem services. It is definitely not possible to apply only one ecosystem service assessment method within the framework of national ecosystem assessment. At the same time, it is not possible to focus only on one type of ecosystem service value, because this unified approach would lead to a significant distortion of the range of benefits that ecosystems provide to human society.

According to the basic distinction, the types of economic values are distinguished into useful and non-useful values. Useful value can be either tangible (food, water, fuel) or intangible (recreation, aesthetic enjoyment of the environment). Intangible utility values such as recreation or the aesthetic value of ecosystems usually require the application of other valuation approaches than direct benefits. Similarly, determining non-useful values of ecosystems (reference value, existence value) or determining option value requires the application of alternative economic approaches for the valuation of non-market goods and services.

There is a long history of valuing nature and many different approaches have been used in the past. Liu et al.[31] track the milestones in the history of ecosystem services valuation and Bartelmus[32] shows the different possible conceptual stages between the two extremes (the pure economist and the pure environmentalist). Despite the criticisms of these approaches, there is no economic or monetary estimate of ecosystems or ecosystem services with absolute validity: any valuation exercise is always context-related. The aim is not always to attribute an absolute monetary value to nature, but monetary valuation of ecosystem services is useful if the purpose of the valuation of ecosystem services and the subsequent application of the results are clearly defined.[33]

Each method has its strengths and limitations and, often, a combination of approaches is used to provide a more comprehensive valuation of ecosystem services based on the specific context and available data. The use of economic methods to evaluate ecosystem services is well-known. For use in the bioeconomy, they have their advantages and disadvantages, just as in other economic systems. Table 7.2 presents the possible methods which may be used for the assessment of ecosystem services of sectors of the bioeconomy.

Table 7.2 The possible economic valuation methods for the assessment of ecosystem services of sectors of the bioeconomy. Adapted from Grizzetti et al., 2015[34]

Approach	*Valuation method*	*Description of the method*
Cost-based	*Damage cost avoided*	Method that values an ecosystem service estimating the damage that might be incurred if this service disappears.
	Replacement cost	Method that uses the cost of a substitute for an ecosystem as a proxy for the value of services provided by this ecosystem.
Revealed preferences	*Travel cost*	Survey-based technique that uses the cost incurred by individuals taking a trip to a recreation site as a proxy for the recreational value of this site.
	Hedonic price	Method that assigns the value to an environmental characteristic of an ecosystem by looking at differences in property prices.
Stated preferences	*Contingent valuation*	Survey-based technique in which respondents answer questions regarding their willingness to pay for an environmental service or a change in this environmental service.
	Choice experiment	Survey-style technique in which respondents are asked to state their choice over different hypothetical alternatives (alternatives consist in a combination of attributes of an ecosystem and a price associated to this combination).
Benefit transfer	*Unit value transfer*	Method that values an ecosystem service by transferring a monetary value derived from another study (and from another site).
	Adjusted unit value transfer	Method that values an ecosystem service by transferring a monetary value derived from another study, this value being adjusted using an ad-hoc factor to account differences between the two sites.
	Value transfer functions	Method that values an ecosystem service using a value function estimated from another site.
	Meta-analytic value transfer functions	Method that values an ecosystem service from a function estimated through statistical regression analysis of many primary valuation studies.

7.4 Implementation in the decision-making process: Ecosystem services as a comprehensive system of indicators for valuation of the impacts of economic and political measures. A multifunctional approach

Ecosystem services converge with the bioeconomy in terms of both their goals and their tools and mechanisms. This applies both to ecosystems as sources of ecosystem services, and to socio-economic systems that use, manage and therefore directly and indirectly modify ecosystems. Due to the complexity of the concept of ecosystem services, the bioeconomy is only one of the ways to use ecosystem services. Both resources and products, as well as social and economic benefits, are described within the framework of the concept of ecosystem services.

However, the main way in which the bioeconomy affects the concept of ecosystem services is by emphasising the importance of selected ecosystem services for society. This is mainly a question of the provisioning of Ecosystem Services (source of materials, food, energy purposes, etc.), but also relates to the regulation of ecosystem services, some of which have received little attention to date. If circularity is an important feature of the bioeconomy, then the return of nutrients to the soil through waste from the life cycle of materials and food must naturally play an important role in this cycle. At the level of environmental policy, the bioeconomy underlines the main role of ecosystem services, which is the improvement of human well-being.

So where does the bioeconomy share the same goals as ecosystem services? In addition to the dominant areas of forestry and agriculture, there is also the area of water management, especially fisheries. These sectors are then followed by overarching, interdisciplinary or linked fields and topics such as landscape management, regional development, circular cities, measures for adaptation to climate change, waste management and others. Figure 7.3 presents the main economic sectors and human activities, managing the resources of ecosystem services used and/or produced within the bioeconomy.

Figure 7.3 Examples of primary economic sectors and human activities, managing the resources of ecosystem services, used and/or produced within the bioeconomy.

Source: own elaboration.

7.4.1 Implementation of the concept of ecosystem services in the sector of the agricultural bioeconomy

Agricultural ecosystems are actively managed by humans to optimise the provision of food, fibre, and fuel. These ecosystem services from agriculture, classified as provisioning services by the recent Millennium Ecosystem Assessment, depend in turn upon a web of supporting and regulating services as inputs to production (e.g., soil fertility and pollination). Agriculture also receives ecosystem dis-services that reduce productivity or increase production costs (e.g., herbivory and competition for water and nutrients by undesired species). The flows of these services and dis-services directly depend on how agricultural ecosystems are managed and upon the diversity, composition and functioning of remaining natural ecosystems in the landscape.[35]

The interconnection and influence of agricultural ecosystems and ecosystem services is presented in Figure 7.4. For agricultural management, it is not only the ecosystem services that are important, but also the effect of the ecosystem services of the surrounding ecosystems on the agricultural land. Their ability to produce ecosystem services depends on these influences, as well as on the internal characteristics of agricultural ecosystems. In the vast majority of cases, there is a unilateral preference for productive ecosystem services. Other ecosystem services are mainly brought to agriculture by a mosaic of other types of ecosystems (for example, protective shelterbelts, retention belts or permanent grasslands).

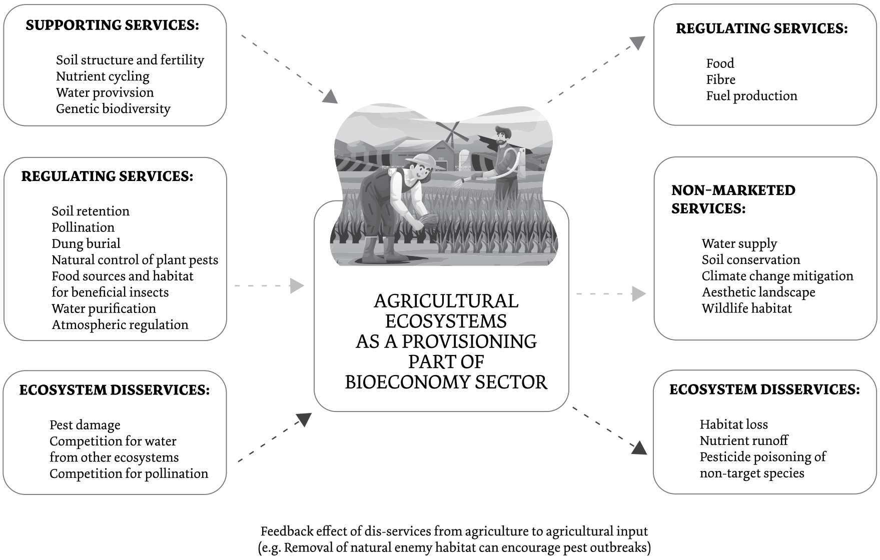

Figure 7.4 Ecosystem services and dis-services to and from agriculture ecosystems as a provisioning part of a bioeconomy sector.

Source: Own elaboration based on Zhang et al.[36]

Note: Gray arrows indicate services, whereas Black arrows indicate disservices.

Different agronomic practices and agroecosystems have different capacities to produce ecosystem services. Biodiversity is a key factor. A common assignment for the application of the concept of ecosystem services in agriculture is to compare the Ecosystem Services of conventional agriculture and organic farming.

One of the data sources for the possibility of evaluating the differences between ecological and conventional farming is the database of the European Farm Accountancy Data Network (FADN EU). This database provides data on a representative set of agricultural enterprises with regard to their management and the structure of revenues and costs, including, for example, the share of crop production, livestock production or subsidies on the revenue side and costs of fertilisers or plant protection products on the cost side. This data can be obtained, amongst other things, classified into ecologically and conventionally managed enterprises, while also providing the possibility of determining the production area and/or choosing the location of the enterprise in different agroecological conditions. In this context, the need for expression per 1 ha of agricultural land is very important, an option that this resource also provides. All values are available in time series from 2000.

For Ecosystem Services that cannot be evaluated directly or indirectly using data from FADN, appropriate non-market valuation methods can be implemented, e.g. Willingness to Pay, shadow prices, saved costs, etc. The application of these methods can be used for the monetisation of social benefits, enabling their subsequent summarisation and expression of differences in individual management systems.

Compared to conventional agriculture, conservation agriculture, as another approach to agriculture and the bioeconomy, improves several aspects of cropping systems that can enhance Ecosystem Services. Conservation agriculture improves soil structure and typically leads to reduced soil erosion and surface runoff. It is particularly advantageous in drier regions, where it helps to increase soil water storage and maintain greater crop yield. Compared to the intensive agriculture, conservation agriculture also generally enhances soil organic carbon storage, particularly in the topsoil.[38] This can help with climate mitigation through carbon sequestration, reduced emission of greenhouse gases (CO_2, CH_4, N_2O) and water regulation. However, not all experiments report that conservation agriculture has a positive impact on Ecosystem Services. This can be due to the duration of experiments, as well as cropping system, climate, soil type and land management practices. Therefore, understanding and decoding the complexities involved in soil–climate-management-dependent conservation agriculture is important and requires a multidisciplinary approach. Whether conservation agriculture can deliver significant Ecosystem Services under a climate change scenario is also an important question that needs to be addressed by studying the differential effects of temperature, warming and changes to rainfall patterns on soil processes and Ecosystem Services in conservation agriculture -adopted farms/experiments[39] (Table 7.4).

Figure 7.4 and Tables 7.3 and 7.4 clearly show the position of ecosystem services within the bioeconomy – Ecosystem Services are an information tool that clearly describes, interprets and documents a comprehensive overview of the effects and benefits of the entire range of possible economic decisions or social requirements and thereby enables these decisions to be optimised. Conventional (mostly linear) agriculture has led to several drawbacks such as biodiversity loss, climate change, erosion, and pollution of air and water. A potential solution is to implement management practices that utilise and increase the level of provision of ecosystem services such as soil fertility and biological regulation and integrated protection. Figure 7.5 supplements and concretises this mechanism with a comparison on the scale of best (immediate economic) management practices and "responsible" management with their impacts on biodiversity and the ecosystem services/ecosystem dis-services ratio.

Table 7.3 Major ecosystem services (ES) and dis-services (EdS) to agriculture, the scales over which they are typically provided, and the main guilds or communities whose activities typically supply them (modified[37])

ES or EdS	*Field*[a]	*Farm*[b]	*Landscape*[c]	*Region/globe*[d]
Ecosystem services				
Soil fertility and formation, nutrient cycling	Microbes; invertebrate communities; legumes	Vegetation cover		
Soil retention	Cover crops		Riparian vegetation; floodplain	Vegetation cover in watershed
Pollination	Ground-nesting bees	Bees; other pollinating animals	Insects; other pollinating animals	
Pest control	Predators and parasitoids (e.g. spiders, wasps)	Predators and parasitoids (e.g. spiders, wasps, birds, bats)		
Water provision and purification		Vegetation around drainages and ponds	Vegetation cover in watershed	
Genetic diversity	Crop diversity for pest and disease resistance	Species diversity – wild varieties		
Climate regulation	Vegetation influencing microclimate (e.g. agroforestry)	Vegetation influencing microclimate	Vegetation influencing stability of local climate; amount of precipitation; temperature	Vegetation and soils for carbon sequestration and storage

(*Continued*)

Table 7.3 (Continued)

ES or EdS	*Field*[a]	*Farm*[b]	*Landscape*[c]	*Region/globe*[d]
Ecosystem disservices				
Pest damage	Insects; snails; birds; mammals; fungi; bacteria; viruses; weeds	Insects; snails; birds; mammals; fungi; range weeds		
Competition for water from other ecosystems	Weeds	Vegetation cover near drainage ditches	Vegetation cover in watershed	
Competition for pollination services	Flowering weeds	Flowering weeds	Flowering plants in watershed	

[a] Services provided from within agriculture fields themselves.
[b] Services provided from farm property, but not necessarily in active fields themselves.
[c] Services provided from landscape surrounding typical farms, not from farmer's property.
[d] Services provided from broader region or globe.

Table 7.4 Comparison of ecosystem services typically provided by conservation agriculture versus conventional farming practices (based on Jayaraman et al.[40])

Ecosystem services	*Conservation agriculture*	*Conventional farming practices*
Provisioning services		
Crop yields	↘ → ↑	↑ ↘ →
System productivity	→ ↗ ↑	↑ ↘ →
Water storage	↑	↓
Regulating services		
Erosion control	↑ ↓	↑
Soil fertility/health	↗ ↓ ↔	↘ ↓
Greenhous gas emission regulation	↑ ↓ ↔	↑
Clear air	No residue burning ↑	Large scale residue burning ↓
Clean water	↑	↓
Moderation of extreme events (droughts/floods)	↑	↓
Supporting services		
Soil biodiversity	↑	↓

↑ Indicates higher; ↓ Indicates lower; ↔ No effect; ↘↗ indicate more gradual change over time

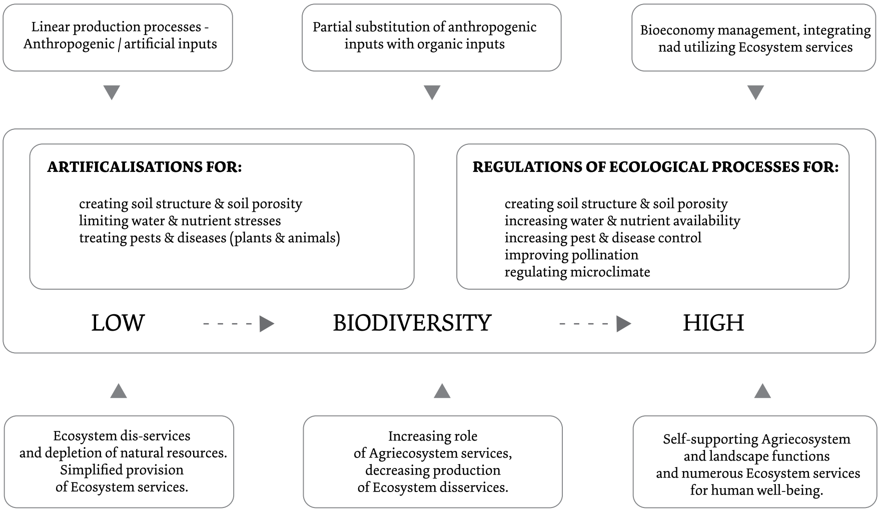

Figure 7.5 From conventional agriculture's drawbacks to ecosystem service solutions.

Source: Own elaboration based on Duru et al.[41]

Compared to the efficiency/substitution paradigm, biodiversity-based agriculture is more knowledge-intensive and requires implementing a more systemic and holistic view of agricultural systems. Currently, biodiversity-based agriculture is marginal, given the current high degree of specialisation of farms and regions in productive rural zones.[42]

Crops and livestock and farmed or wild-harvested trees and aquatic species all clearly contribute directly to food security and livelihoods. In many cases, they also provide other services that support food and agricultural production. For example, a tree or an herbaceous crop plant may help to protect the soil against erosion or to create a favourable microclimate for other components of the production system, while a farmed animal may remove weeds or provide manure to fertilise crops, or a filter-feeding mollusc raised in aquaculture may contribute to water purification. Many of the other species that live in and around production systems also make relatively direct and clearly identifiable contributions to food and agriculture, for example the role of bees in pollination or that of ladybird beetles in removing aphid pests from crop plants. However, the health of a crop, grassland, forest, marine or freshwater production system is influenced by an enormous range of ecological processes, many of which are complex and not well understood. These processes operate on a variety of scales, ranging from very local to global, and cross the boundaries between production systems, between the sectors of food and agriculture and between managed and unmanaged ecosystems. To provide a concrete example, a crop plant may benefit from soil-maintaining services provided by earthworms living in the immediate vicinity, from pollination services provided by insects that depend on the biodiversity present in hedgerows or uncultivated areas at the edge of the field, and from climate regulating services provided by distant forest, grassland, or ocean biodiversity.[43]

Biodiversity for food and agriculture cannot be considered in isolation from the humans that manage production systems. Farmers, livestock keepers, forest dwellers, fish farmers and fishers constantly engage with their environments, shaping them to varying degrees and utilising components of biodiversity in different combinations to meet their needs. Many domesticated species have been used, developed, and maintained by humans for thousands of years.[44]

7.4.2 Implementation of the concept of Ecosystem services in forest management

There is a long tradition of the use of Ecosystem Services in forestry as a sector of the bioeconomy. Forest management is always implemented from the point of view of one or more ecosystem services. One of the basic and most preferred Ecosystem Services is wood production. Equally important, however, are recreational Ecosystem Services or regulatory Ecosystem Services, mutually influencing individual components and processes in forest ecosystems as ecosystem functions, ranging from the preservation of biodiversity to air quality, soil properties and runoff conditions.

There are also circular elements inherent to forest management (as part of the bioeconomy). Nevertheless, it is possible to distinguish between approaches that systematically utilise them within the 'close-to-nature' forest management and systems whose circularity is practically exclusively due to artificial forest regeneration. A typical example of assessing adherence to bioeconomic principles in forest management is the comparison between forests of different age classes regenerated by clearcutting (often used in monocultures and forest plantations) and selection forests. The age-class forest is an example of more or less linear forest production, where a large majority of biomass and nutrients are removed from the area during harvesting. Subsequently, it is necessary to reuse seedlings grown in forest nurseries. However, part of this system is the carbon storage when using wood, for example, as a building or decorative material, and, then, the release of carbon when using firewood. In the case of selection forest management, the production of ecosystem services is more balanced, but mainly continuous. Within the dynamics of natural processes, the immediate availability of socially targeted ecosystem services may be lower (e.g., timber production or the amount of carbon sequestration) than in the case of intensively managed forest areas. However, it ensures the balanced provision of ecosystem services over the long term.

The following text presents a possible example of using the assessment of ecosystem services and forest functions for decision-making processes in forest management as a typical branch of the bioeconomy. This assessment allows the effectiveness of bioeconomic measures to be evaluated compared to conventional steps and thus contributes to optimising the benefits of the bioeconomy. Long-term records and information on forest stands are an advantage of forest management from the point of view of the calculation of ecosystem services. If we have available data on habitat conditions (often expressed by forestry typology or geobiocoenology), we know the input data for calculating ecosystem functions. What is the difference between ecosystem functions and ecosystem services? This can best be illustrated by the example of melting snow. Melting snow is a process that happens in the ecosystem. As well as the daily course of temperatures, which will be different in the forest and in the open countryside, the influence of the forest cover on the snowmelt process is an ecosystem function that happens whether or not it is used by humans. In the event that forest stands slow down the melting of snow and thereby reduce the outflow of water from the basin, its speed and thus the flood wave, which can threaten human health and property, this is an ecosystem service. In general, the whole process is graphically presented in Figure 7.6 Inputs into the process of production of forest ecosystem services are shown on the left – characteristics of forest stands and forest management measures that influence these characteristics. This is, by the way, an argument against the philosophical opinion and resistance of some authors that the concept of ecosystem services is anthropocentric and therefore not sufficiently conscious. The concept of ecosystem services is, above all, complex, aware of the biophysical nature of the entire system.

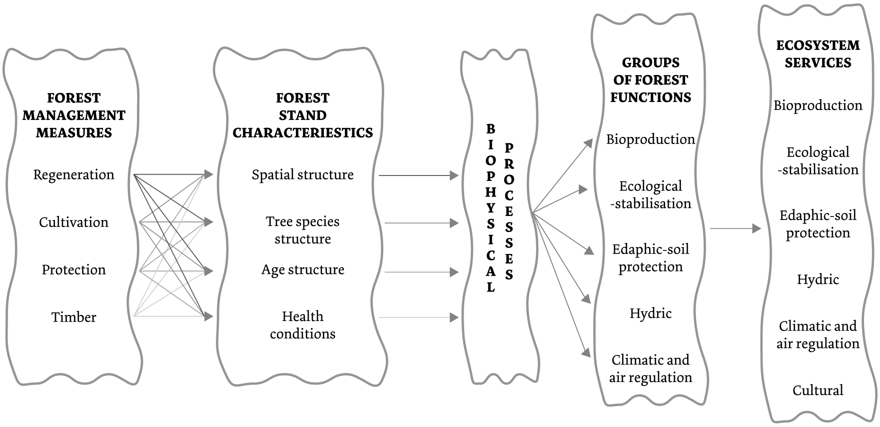

Figure 7.6 Impact of forestry interventions on forest ecosystem services.

Source: Own elaboration.

Examples of the forest functions and ecosystems on the right of Figure 7.6 are provided in Figure 7.7 – we refer to ecosystem functions that bring benefits to human society as ecosystem services. Without knowledge and quantification of ecosystem functions, we cannot quantify the potential (ability) of ecosystems to provide ecosystem services.

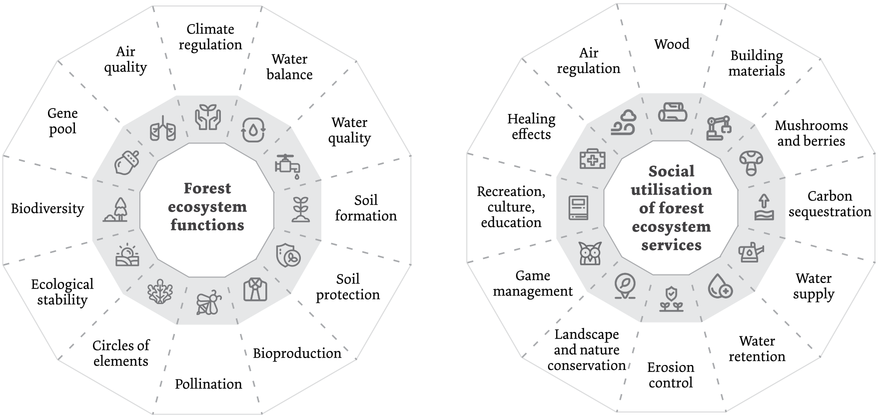

Figure 7.7 Ecosystem functions converge with forest ecosystem services.

Source: Own elaboration based on Schneider, Holušová et al., 2016[45]

Forest stands, like other ecosystems, can be assessed using a number of general methods, listed in Section 7.3. A specific method for assessing forest ecosystem functions is the Quantification and Quantitative Assessment of Forest Functions method according to Vyskot et al., 2003,[46] adapted in 2011 for structurally differentiated forests by Schneider.[47] The method is based on detailed long-term forestry inventory data for all forest ecosystems in the Czech Republic. These conditions are classified into seven value grades. Ecological characteristics of forest stands can be obtained from forest management plans. These characteristics (for example, biotope properties, linked to individuals of forest typology) represent the determination criteria, determining the real potential of forest stands in optimal conditions to produce ecosystem functions. The real effect then represents the real ability of forest stands to produce ecosystem functions. This is influenced, for example, by age, health status or the species composition of forest stands. Building on this evaluation of forest functions and a bridge to ecosystem services is referred to as the factor of current social interest, which summarises the declared social requirements to produce ecosystem services (e.g. water resource protection zones, suburban recreational forests, forests in protected areas, forests below the upper line forests, etc.). Schematically, the entire essence of the biophysical assessment of forest functions according to Vyskot et al.[48] is presented in Figure 7.8.

Ecosystem functions determined in this way can also be evaluated financially. The Ministry of Agriculture of the Czech Republic publishes the average price per cubic metre of wood every year. If we respect this price as the financially expressed value of average wood production, we can use it analogously

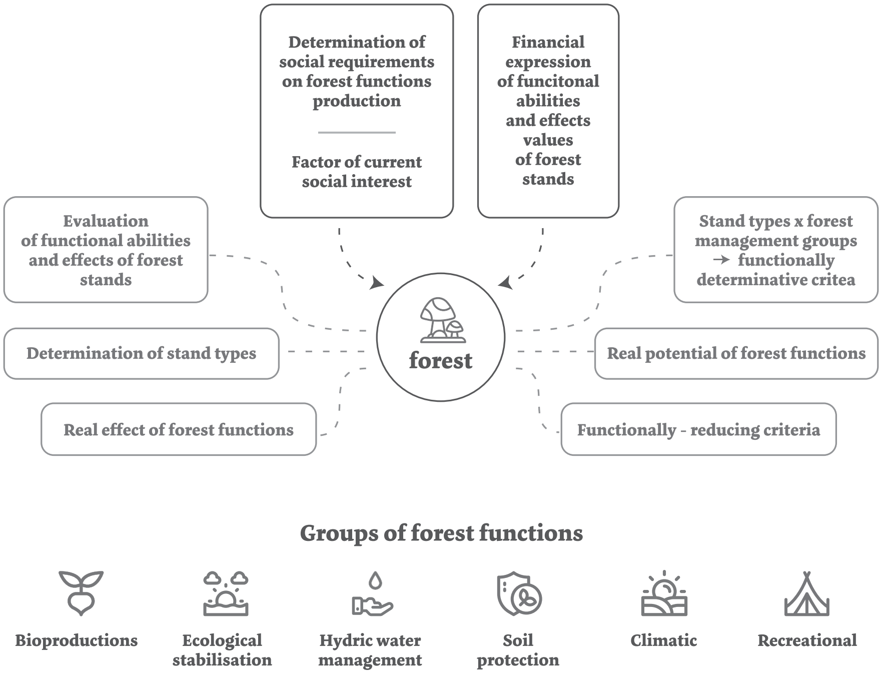

Figure 7.8 Input data for assessment of forest ecosystem functions.

Source: Own elaboration based on Schneider, Holušová et al., 2016[49]

as the financially expressed average value of other ecosystem services. Higher or lower production then depends on this comparative level.

However, the ecosystem services of forests can also be used in a simplified form within the decision-making process of searching for optimal economic processes. Table 7.5 presents this process. Possible restoration procedures are evaluated in terms of all groups of ecosystem services. One is chosen that does not have negative impacts, while, on the contrary, optimal or indifferent effects prevail from the point of view of individual groups of forest functions.

7.4.3 Agroforestry

Agroforestry is a sustainable land management system that integrates trees or woody shrubs with crops and/or livestock in a mutually beneficial manner. It involves intentionally combining agricultural and forestry techniques to create diverse, productive, and resilient systems. Agroforestry is therefore typically focused on the effective use of natural processes, the optimised production of ecosystem services, which are among the typical features and benefits of the bioeconomy.

Table 7.5 An example of the decision-making process – choosing the optimal regeneration procedure in floodplain forests

Group of forest ecosystem functions	*Regeneration process*
Bioproduction (BP)	Use of clear cutting (H) up to 1 ha with a cutting width equal to twice the average stand height.
Eco-stabilisation (ES)	To the maximum extent possible, use natural regeneration within the management systems of shelterwood or selection. However, it is also possible to use small-scale clearcuts.
Hydric-water management (HV)	Shelterwood management system is recommended within 50 m of the source of drinking water. In the rest of the territory, the Partial management system is allowed.
Soil regeneration and protection (EP)	Any of the forest management systems can be used to fulfil the edaphic-soil protection function
Social-recreation (SR)	Optimal stands are species-rich, spatially differentiated mature stands with great areal diversity
Sanitary-hygienic (ZH)	Optimal stands are species-rich, spatially differentiated stands

Forest management system	Groups of forest functions					
	BP	ES	HV	EP	SR	ZH
Clearcutting	I	N	R	I	R	R
Partial	I, O	I	I	I	I	I
Shelterwood	I	O	O	O	I	O
Selection	I, R	O	O, I	O, I	I, R	I

Explanations: O – Optimal procedure, I – Indifferent procedure, R – Function-limiting (retarding) procedure, N – Function-negating procedure

Functionally integrated management	In alluvial forests, from the point of view of functional integration, the Shelterwood forest management system is most suitable. Combination of Partial and Shelterwood systems is also suitable.

The ecosystem services of agroforestry as a bioeconomy benefits are multifaceted:

1 **Variability of the production of supply ecosystem services**: This variability not only provides an economic benefit for farmers and owners, but also brings an output product – biomass for the circular principles of bioeconomic practices and their distribution over time (durability).
2 **Biodiversity conservation**: Agroforestry systems promote biodiversity by providing diverse habitats for various plant and animal species. The combination of trees, crops, and livestock creates niches that support a wider range of organisms.
3 **Soil improvement**: Trees in agroforestry systems contribute to soil fertility through nitrogen fixation, adding organic matter through leaf litter, and preventing erosion with their root systems. This leads to improved soil structure, moisture retention, and nutrient cycling.

4. **Climate regulation**: The presence of trees in agroforestry helps in carbon sequestration, mitigating climate change by absorbing CO_2 from the atmosphere. They also provide shade, reducing temperature extremes and mitigating the impact of climate-related stresses on crops.
5. **Water management**: Trees assist in regulating water cycles by reducing runoff, increasing groundwater recharge, and maintaining water quality. Their root systems can also help stabilise riverbanks and prevent soil erosion.
6. **Economic benefits**: Agroforestry systems offer diversified income sources through the simultaneous production of multiple products such as timber, fruits, nuts, fodder, and medicinal plants. This diversity can increase resilience to market fluctuations and provide a more stable income for farmers.

The perspective of agroforestry as a bioeconomy sector for the future is promising for several reasons:

1. **Sustainability**: Agroforestry systems are environmentally sustainable as they enhance biodiversity, reduce the need for external inputs like fertilisers and pesticides, and improve soil health, thus ensuring long-term productivity.
2. **Resilience to climate change**: The diversity in agroforestry systems makes them more resilient to extreme weather events and climate change impacts. They can better withstand droughts, floods, and temperature fluctuations.
3. **Food security and livelihoods**: With increasing global population and changing climatic conditions, agroforestry offers a way to produce food while preserving natural resources and supporting the livelihoods of rural communities.
4. **Carbon sequestration**: Given the pressing need to mitigate climate change, the ability of agroforestry to sequester carbon in trees and soil makes it a valuable tool in efforts to reduce greenhouse gas emissions.
5. **Environmental restoration**: Agroforestry can also contribute to landscape restoration efforts by rehabilitating degraded lands, preventing desertification, and improving ecosystem health.

Agroforestry therefore appears to be a promising approach to management from the point of view of adaptation measures in the landscape and resilient agriculture and forestry. The benefits of agroforestry, as well as other branches of the bioeconomy, can then be compared precisely through the production of ecosystem services, ecological stability and their continuity, as described above.

7.4.4 Water management and fishery

An important part of the bioeconomy is the management of water resources – natural and anthropogenic formations, surface and subsurface waters. Ponds are a typical example. Although the ponds are small water reservoirs created by man, they have been perfectly integrated into the surrounding landscape since their inception. Ponds are not only a source of fish, but also fulfil a number of non-production functions, which include, for example, the retention of water and nutrients in the landscape, influencing the local climate, recreational and aesthetic functions and, last but not least, the support of biodiversity. In terms of benefits for human society, ponds provide a whole range of ecosystem services. Different stakeholder groups, however, perceive other groups of ecosystem services as priority. The production of fish is especially important for fishing enterprises. Nature conservation authorities see it as a vital support for biodiversity, and tourists and visitors, for a change, see their recreational and aesthetic function as essential. However, e.g. the Třeboň pond system (Czechia) is also important for the Czech Republic as part of its cultural tradition and identity. That is why it is necessary to look for such economic procedures that will enable both their economically sustainable management and also the provision of non-production ecosystem services.

There are four main steps to addressing this question:

1 environmental – mapping of sources of ecosystem services and their identification
2 ascertaining the social preferences of the target groups of stakeholders
3 determination of economic aspects – cost–benefit analysis, financial expression of the value of ecosystem services
4 organisational charts of the effects of individual measures on the values of ecosystem services, definition of optimal economic (bioeconomic) procedures

The result of the evaluation of the ecosystem services of ponds is the determination of the priorities of individual groups of stakeholders; the potential of ponds to fulfil these ecosystem services and take into account other ecosystem services. Based on these priorities, they define compromise principles for the management and use of these important water bodies. This methodological procedure can be applied not only to ponds, but also to other water bodies in the landscape.

7.4.5 Landscape management and regional development

Landscape management and regional development are not usually listed among the disciplines that are linked to the bioeconomy. However, these are complex interrelated disciplines, built on the interrelationship of ecosystems and socio-economic systems, similarly to ecosystem services and the bioeconomy.

All branches of the bioeconomy affect the entire landscape system of which they are a part. A typical example is water management, which interacts with agriculture, forestry, but also with urban blue-green infrastructure or energy. Table 7.6 presents a wide range of policy instruments that, even with the use of ecosystem services, influence the use of water resources.

Ecosystem services are an important communication and information tool for the decision-making process, planning and evaluation of the impacts of human activities or natural processes or education within all branches of

Table 7.6 Policy instruments relevant for ecosystem services[50]

Category	*Policy instruments*	*Examples/explanations*
Economic instruments	• *Taxes* • *Markets* • *Subsidies* • *Payments for ecosystem services*	• Effluent taxes, water withdrawal fees • Tradable water pollution permits • Subsidies for low water consumption equipment • "Contract for services" i.e. voluntary payment for the delivery of specified ecosystem services. In France payment by the Vittel company to farmers who adopt less intensive farming techniques; in the UK, anglers' payments for improvements to river water quality (angling passport)
Voluntary approaches	• *Private agreements* • *Public voluntary schemes* • *Negotiated agreements*	• Unilateral commitments made by polluters or resource users, multilateral agreements between polluters and pollutes or between resource users • Voluntary programmes developed by public bodies such as environmental agencies, to which economic agents (individuals, farmers, firms) are invited to participate • Agreements usually created out of a dialogue between government authorities and economic agents (individuals, farmers, firms), typically containing a target and a timetable for reaching that target
Regulations	• *Norms and standards* • *Restrictions on use and access* • *Liability rules*	• Minimum water flows, maximum pollutant concentrations in watersheds • Legal possibility for public authorities to restrict or to limit access or use of water resources • Legal obligations for the responsible party to bear the costs of restoring the environment
Information tools	• *Education campaign* • *Use of media* • *Eco-labelling of products*	• Campaigns to raise awareness of children about water issues • Use of any kind of media for informing populations about water issues • Water-saving labelling programme for products and services which are helping to reduce water use (Smart WaterMark in Australia)

bioeconomy. They help the process to be more efficient, as it provides generally understandable information about the value of natural resources that are not part of market mechanisms. A disadvantage of the concept of ecosystem services is the large variability of input data and calculation methods. The advantages are the complexity of the assessment through a combination of economic, ecological and sociological principles, as well as versatile applicability.

The possibilities and methods of utilising ecosystem services in the bioeconomy are neither new nor unknown. Most of these utilisation methods have been tested before the systematic use of the term bioeconomy and the implementation of its principles. However, what is innovative is their utilisation in the decision-making process of the bioeconomy. Ecosystem services enable:

- precise expression of the value of bioeconomic products and processes for society;
- assessment of the impacts of economic measures on ecosystems as sources of ecosystem services and functions;
- more precise decision-making in the choice of economic measures;
- expression of the economic efficiency of management through environmental accounting;
- clearer and more comprehensive interpretation of the benefits of the bioeconomy for the general public;
- specifically, the choice of economic measures that support the adaptation of environmental and socio-economic systems to climate change.

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8 Environmental problems of the bioeconomy

Tomáš Kopta, Angelika Kliszcz and Agnieszka Józefowska

8.1 Introduction

Today's society has increasing needs for good and services; at the same time, however, we are experiencing difficulties due to resource scarcity, which are having an impact on financial assets, energy reservoirs, raw materials and environmental capability. Therefore, the contradiction between expanding needs and finite resources poses one of the biggest challenges that society, organisations and people in general presently face.

An integral part of the assessment of the bioeconomy should be linked to an awareness of urgent environmental issues. According to Nagarajan,[1] the bioeconomy deals with the production and utilisation of biological resources, innovative biological processes, and principles to sustainably provide goods and services across all economic sectors. The bioeconomy is being integrated into diverse sectors, encompassing industry and agribusiness branches like agriculture, forestry, fisheries, food production, pulp and paper manufacturing, as well as segments of the chemical, biotechnological and energy sectors.[2] Although the bioeconomy relies on renewable bioresources, it does not inherently guarantee sustainability or resolve related issues. Some suggest that this economic model could introduce new environmental challenges.[3] Oláh[4] point out that a notable rise in biological resource consumption may diminish ecosystems' ability to meet human requirements. The research findings highlight the link between the bioeconomy and significant socio-environmental sustainability problems. These include the consequences of direct and indirect land use changes, declining ecosystem quality, the spread of pollutants, and an amplification of water shortage challenges.

These issues are often the subject of research and policy discussions. The main reasons for environmental problems include land use changes and deforestation, pesticide and chemical use, water resources, carbon balance, and, connected to all the factors mentioned, soil biodiversity (Table 8.1).

One of the main environmental threats that can be partly solved by good bioeconomy practices is land transformation and type of land use. As we know, human practices related to land management have significantly transformed landscapes worldwide, impacting the diversity of plants, animals, microbes, soil quality and ecosystem services.[15] On the one hand, in less developed

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Table 8.1 The main environmental problems of the bioeconomy and their main causes

Environmental problem	*Causes and examples*
Land use change and deforestation	Converting forests into agricultural fields or converting semi-natural/agricultural areas into urban zones and transport infrastructure[5]
Soil contamination	Emissions from industry factories surrounded by agricultural fields[6]
Food contamination and its low-quality	Deposition of pesticide residues, heavy metals and nanoplastics in the agroecosystem[7]
Soil salinisation, eutrophication, acidification	Overuse of mineral fertilisers[8]
Water shortages in the soil	Deficiency in occurring rainfall and plough sole, lowering of groundwater, lack of an appropriate number of retention reservoirs, bare soil[9]
Soil organic matter degradation	Avoiding retention of crop residues and cover crops in the fields and depriving the soil of its microbiome by monoculture crops, tillage and practices that reduce soil health[10]
Topsoil losses	Farming on slopes, soil erosion processes caused by wind, water and tillage[11]
Invasive species	Globalisation, global warming[12]
Loss of biodiversity	Application of pesticides, monoculture cropping, expansions in invasive species[13]
Multi-drug resistance among bacteria in soil, water, air	Overuse of pesticides and antibiotics causes higher concentrations of active substances and their metabolites in the environment, to which bacteria respond with adaptive mechanisms[14]

countries, the agricultural land area is expanding while agricultural practices remain at a low level. On the other, in developed countries, agricultural areas are being urbanised with the construction of houses and roads (Figure 8.1).[16] Key sectors like agriculture and related management practices play an important role in affecting nutrient cycling, carbon stocks and biodiversity. The increasing needs related to the expanding human population and ongoing development exert substantial pressure on land use, especially in less-developed regions (e.g. compare Africa and Europe in Figure 8.1).

In turn, in well-developed economies, consumer preferences are not without significance, because constant demand for the same type of goods forces unsustainable land use, e.g. in the case of the wheat sector. Food production stands as a significant contributor, accounting for a quarter of the world's greenhouse gas emissions.[17] The impact varies across different product groups, encompassing both direct costs and environmental repercussions. An illustration displaying the greenhouse gas emissions from 20 food products throughout their supply chain is presented in Figure 8.2 and shows the varying environmental footprints of these products, shedding light on the diverse impact of food production on greenhouse gas emissions.

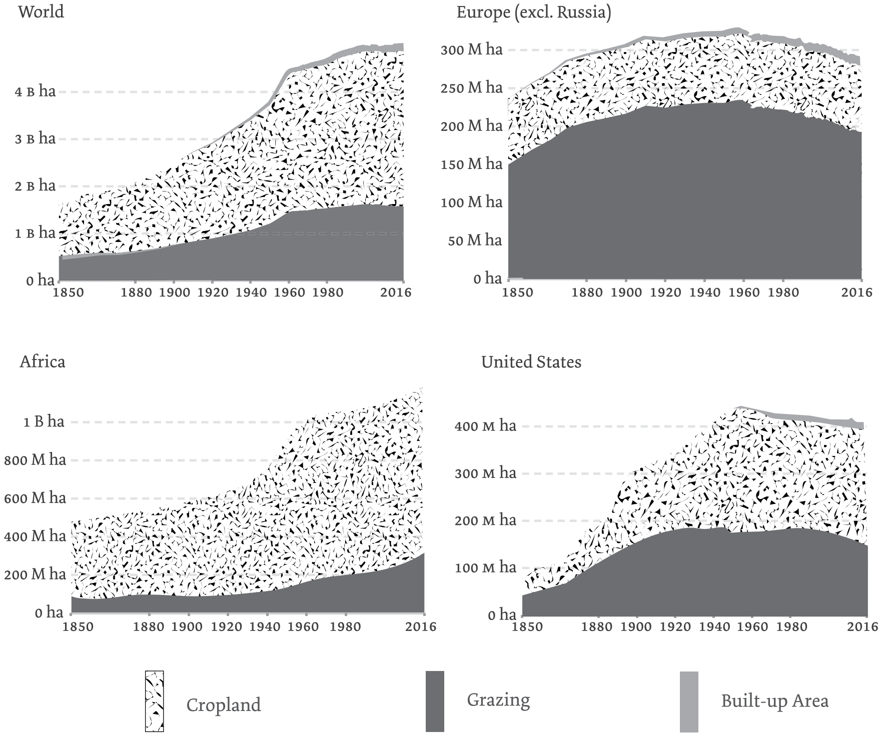

Figure 8.1 Land use transformation from 1850 to 2016 showing total land area used for cropland, grazing and built-up areas.

(data source: OurWorldInData, History of the Global Environment).

Note: Graphs are on different scales.

The environmental consequences of monoculture wheat cultivation are well-known in the literature.[18] Therefore, to strengthen the bioeconomy, the range of cultivated plants and bred animals should be broadened on the demand side, meaning wider consumer food preference. That force in the bioeconomy will lead to the diversification of agricultural production and positive environmental outputs of agriculture, as well as having an effect on food security.[19] Despite advancements in biotechnology, mechanisation and inputs, the land area available for cultivation remains constant, intensifying land use (Figure 8.1) and directly affecting ecosystem quality.

Addressing these environmental problems in the bioeconomy requires a combination of sustainable practices and technological innovations to minimise negative impacts. In this chapter, we will try to present several promising solutions that seek to merge agricultural production with environmentally sustainable practices.

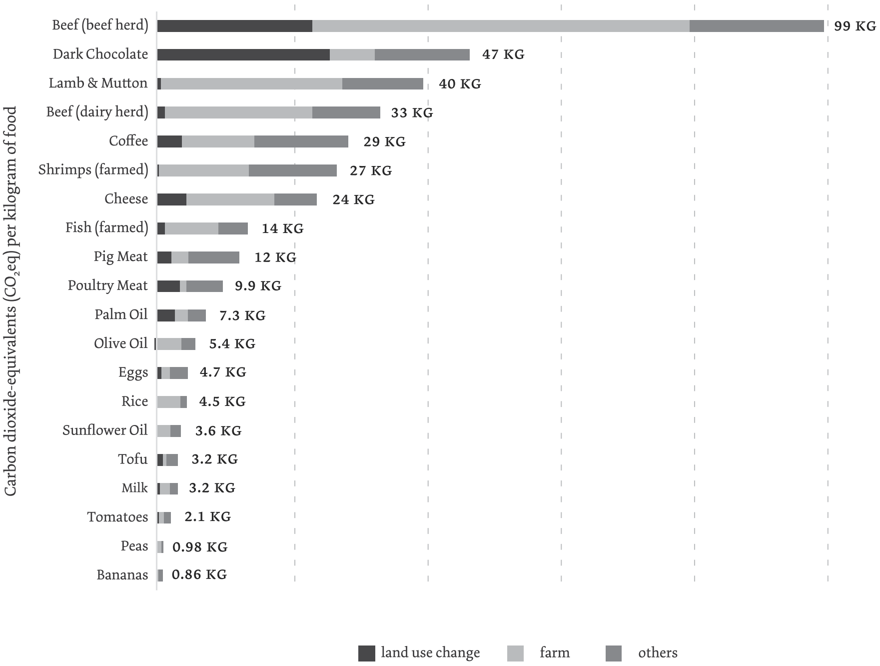

Figure 8.2 Greenhouse gas emissions across the supply chain.

(data source: OurWorldInData).

8.2 Monoculture cultivation and its negative consequences

8.2.1 Negative consequences of monoculture farming on farm biodiversity

According to Power and Follett,[20] monocultures in agriculture offer several key benefits. Firstly, they allow for the efficient use of specialised machinery designed for a single crop, resulting in reduced equipment costs per unit of production. Additionally, monoculture enables farmers to specialise in production techniques tailored to the specific conditions of their land, optimising practices like fertilisation, pest control and tillage. This specialisation not only maximises crop yields but also simplifies the marketing process, as farmers only need to focus on one market. However, it is important to note that monoculture also has limitations.

Agroecosystems are inherently unstable and susceptible, mostly as a result of the widespread usage of monocultures. Monocultures may reduce soil fertility, promote the spread of plant diseases, and significantly increase weed and insect infestations. Moreover, monocultures pose labour difficulties and economic risks linked to heavy reliance on a single crop. This practice concentrates resources on specialised pests and expands the areas accessible to invading pests. This simplification also diminishes environmental niches for natural enemies. As a result, pest outbreaks frequently occur when a significant influx of invading pests coincides with reduced populations of beneficial insects, favourable weather conditions and susceptible stages of the crops.[21] High-intensity agricultural production systems also lead to the simplification of agricultural landscapes and subsequent removal of non-target vegetation habitats, causing a decline in biodiversity. Intensive agriculture thus creates unfavourable conditions for natural pest enemies.[22] It is therefore necessary to consider the aspect of landscape complexity to ensure an adequate presence of "semi-natural" landscape elements serving as a source of antagonists, such as planting hedgerows, sowing flowering strips, installing shelters for beetles, and so on.[23] According to Boller,[24] ecological infrastructures on the farm (so-called ecological compensation areas) are the most important tool for the full utilisation of the "functional biodiversity" service, especially for maintaining biological protection. Many studies have shown that, in complex landscapes with a high proportion of non-crop vegetation, populations of natural enemies are higher, and, at the same time, pest pressure is lower.[25] The diversity of plant and insect species in permanent cultures such as vineyards has also been shown to be improved by natural and semi-natural environments.[26] In monoculture farming, pesticides are often used, which can harm beneficial insects, pollinators, birds, and other animals and plant species.[27]

Monocultures, mainly in industrialised countries, are commonly used practice and they have a number of disadvantages. When biodiversity declines, as a result of monocultural practice, the crop will be more susceptible to pest and diseases which leads to increased need of pesticides. We are also facing problems with water pollution and damaged water ecosystems as a result of fertiliser overuse. Current monocultural methods lead to soil degradation and nutrient depletion and also threaten the long-term viability of agricultural production (Table 8.1). Growing environmental awareness, along with worries about the ecological consequences of unsustainable agricultural techniques, has led to a decrease in the use of mineral fertilisers in industrialised countries such as Europe. In contrast, less industrialised countries such as those in Africa have seen a significant increase in the usage of mineral fertilisers. As a result, by 2020, Europe's use of phosphate had surpassed Africa's by 1.5 times, with the figure being over 3 times more for nitrogen, and over 2000 times more for potassium (see Figure 8.3).

8.2.2 Pesticide residues and heavy metal pollution

Similarly, with growth in population, we can observe considerable increase in businesses using agrochemicals. This leads to stronger dependency of agriculture on agrochemicals when slowing pest and weeds issues. Therefore, pesticides have an important role in agriculture by controlling weeds, diseases and pests.[28] According to Syafrudin,[29] the amount of pesticides used worldwide is close to 2 million metric tonnes. Research done by Hassaan and El Nemr[30] indicates that, of this notable quantity of pesticides, around 17.5% is composed of fungicides, 29.5% is insecticides, 47.5% is herbicides, and the

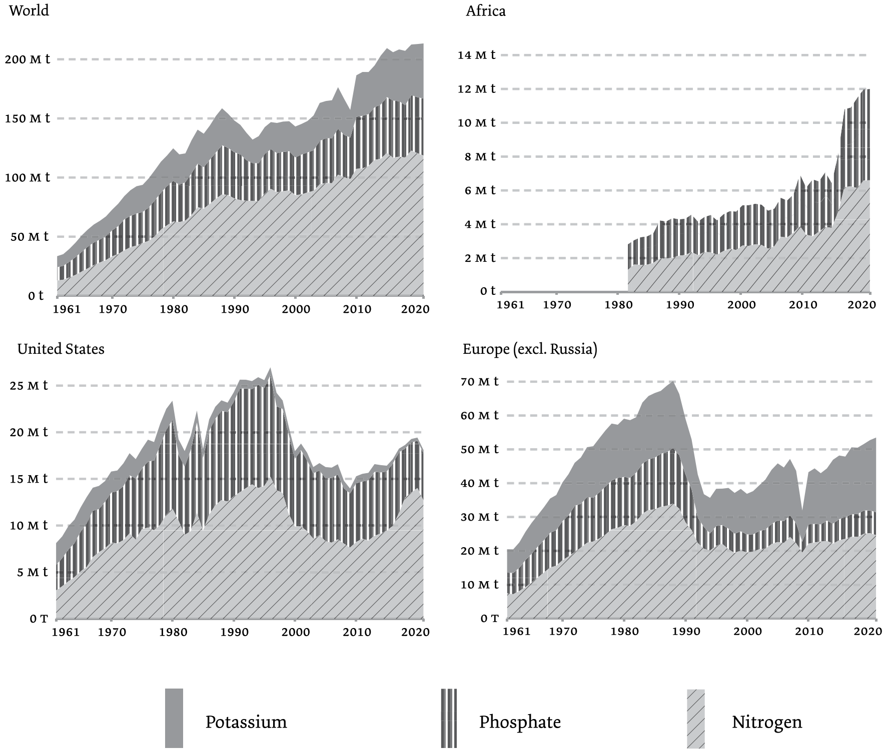

Figure 8.3 Fertiliser production by nutrient type (potassium, phosphate, and nitrogen) from 1961 to 2010.

(Data source: OurWorldInData, Food and Agriculture Organization of the United Nations).

Note: Graphs are on different scales.

remaining 5.5% comes from various other pesticide categories. Although plant protection products have the promise of enhancing agricultural output, the overuse of these compounds raises considerable concerns about possible damage to humans, wildlife and the environment.[31] The development of pesticides use worldwide is presented in Figure 8.4.

Despite the frequent discussion about pesticide residues and their influence on human health, the risks connected with the combination and synergistic effects of these compounds remain little understood. Pesticide exposure, whether deliberate or unintentional, can have both immediate and long-term consequences, as demonstrated by the studies by Ore et al.[32] and Kocourek et al.[33] The European Food Safety Authority[34] takes proactive measures by conducting extensive yearly food testing, methodically identifying and monitoring pesticide residues, and ensuring food safety. Of the 13,845 samples analysed in 2021, 41.9% of samples had quantified results and 27% contained more than one quantified pesticide. Table grapes (22.2%), bananas (18.5%), grapefruits (18.4%) and sweet/bell peppers (12.8%) were the food products with the highest

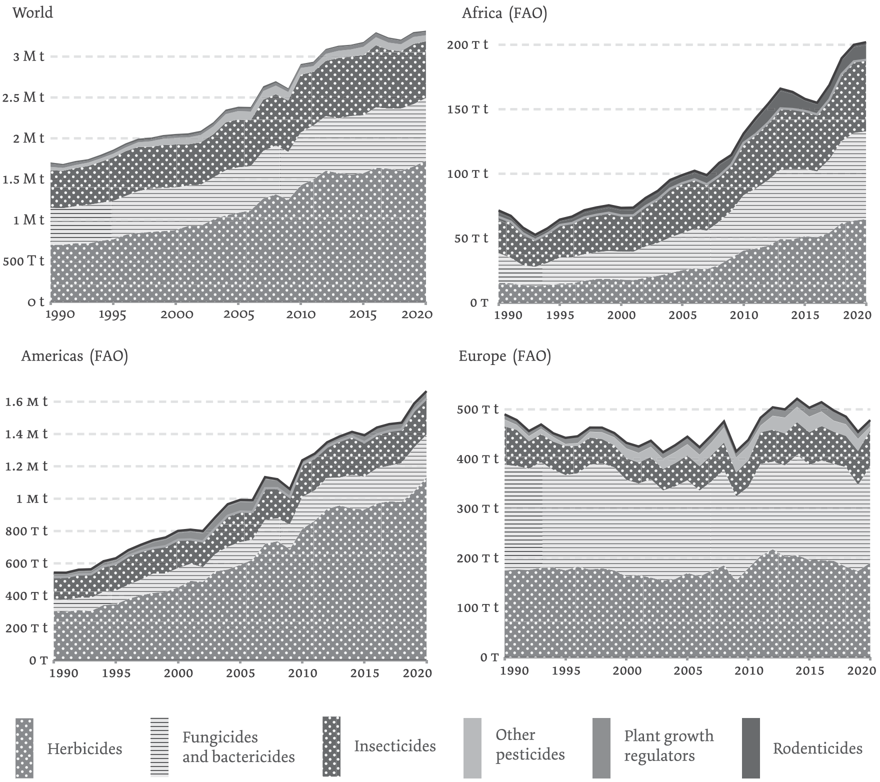

Figure 8.4 Pesticide use worldwide and in selected regions with breakdown by pesticide type.

(Based on data from OurWorldInData).

Note: Graphs are on different scales.

number of samples with multiple residues. This discovery highlights the necessity for extensive monitoring and control techniques.

Heavy metal contamination in crops is mostly caused by the use of fertilisers and copper-based plant protection agents, irrigation with polluted water, and increased urbanisation and industrialisation in agricultural regions.[35] These metals accumulate in important organs such as the kidneys and liver, causing endocrine disruption, oxidative stress, immunotoxicity, cardiotoxicity, teratogenicity and enzyme inhibition.[36] Because metals have different chemical properties and hazardous outcomes, it is important to emphasise that the processes behind their toxicity vary significantly.

Some negative consequences could be solved by the ambitious strategy called for by the Green Deal by 2050. This strategy focuses on nature restoration in all its fields (agricultural landscape, forests, urban areas) and aims to achieve a more resilient and balanced ecosystem. The European Commission is planning to decrease use of synthetic pesticides (by 50% by 2030) and therefore eliminate the related hazards.[37]

8.2.3 Soil erosion

Soil erosion refers to the loss of the topsoil layer through ecological factors like wind or water and agrotechnical practices (i.e. tillage). This unintentional movement of soil from one place to another is intensified by failure to maintain soil cover throughout the year in the field,[38] plant cultivation on slopes[39] or intensive ploughing.[40] The lifespan of soil is shown in Figure 8.5.

Globally, soil erosion was estimated at between 2.5×10^{10} and 4.5×10^{10} tons per year.[42] However, Evans et al.[43] estimated the mean gain of soil layer to be $0.0324\ \mathrm{mm \cdot y^{-1}}$. Therefore, preventing soil erosion through ecology-based solutions for the bioeconomy is highly valuable. In economic terms, there is some evidence in the literature that conservation practices (no-till + cover crops) are associated with lower costs of cash crop production (43% less) compared with the lack of cover crops and tillage applied.[44] Also, managing the Paraná fields in Brazil according to conservation practices (namely no-tillage, crop rotation, contour farming, and agricultural terraces) increased land prices between 10 and 22%, with other conditions remaining the same.[45]

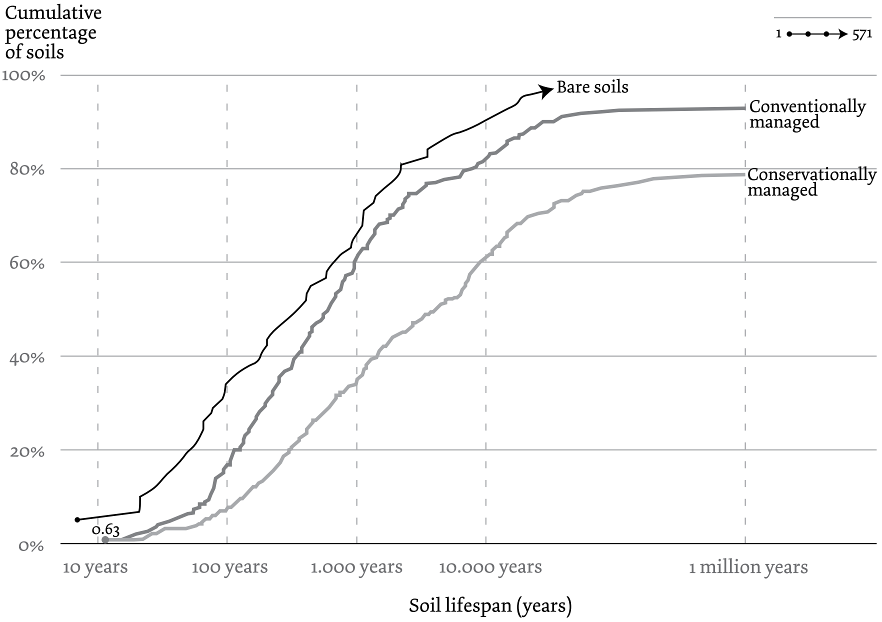

Figure 8.5 Averaged global lifespan of soil. Soil lifespan refers to the estimated duration required to erode 30 centimetres of topsoil, determined by the current erosion rate in a particular area.

(*Source:* OurWorldInData, based on Evans et al.[41])

8.3 Ecology-based solutions for the bioeconomy

8.3.1 Regenerative agriculture

The term 'Regenerative agriculture' (RA) is currently experiencing a renaissance related to the increased interest in public and scientific debate on the problem of loss of fertility of agricultural soils and loss of species, functional and genetic biodiversity. Globally, an estimated 36 billion tons of soil are being lost as a result of various land-degrading practices each year, mainly due to land deforestation for agricultural purposes.[46] Giller et al.[47] noted a significant increase in research articles on RA since 2016. However, the concept of RA was established in the early 1980s in the USA[48,49] and was a response to decades of highly production-oriented and damage-causing agriculture in the United States.[50] White[51] probably provided the shortest and most accurate definition of RA as "*both an attitude and a suite of practices that restores and maintains soil health and fertility, supports biodiversity, protects watersheds, and improves ecological and economic resilience*." A more detailed version was proposed by Moyer et al.,[52] defining RA as *practices that mimic natural ecological processes" and "working to achieve closed nutrient loops, reduction or elimination of biocidal chemicals, greater crop and biological diversity, fewer annuals and more perennials (…) encompassing high standards of animal welfare and worker fairness*".[53] However, there is no complete consensus here on whether pesticides should be completely banned in regenerative practices.

Regenerative practices seem to be decentralised and matched to biodiversity resources tailored to the needs of a specific climate. Evidence of this can be found, for example, in the expansion of the range of cultivated species, i.e. engaging neglected plants in the food production chain within the bioeconomy. An example of such a bioeconomy is India, where approximately 1,403 plant species from 184 families are consumed as reported by Ray et al.[54] The country is naturally predisposed to exploit this potential, but it is nevertheless a good example of strengthening the agricultural sector by using the plant resources of the region. The authors[55] also indicate a list of prioritised neglected plant species suitable for propagation among citizens and compare wild plant dietary preferences between Asian and European people.

From an agronomic point of view, RA stands for enhancing soil with the organic matter with a proper C:N:P:K:S ratio, not damaging soil structure, and accelerating biological, life as well as crop diversification. It is worth mentioning that Conservation agriculture incorporating key regenerative practices[56] seems to be a part of RA. Soil health is pursued mainly through the development of biologically relevant practices and therefore also monitoring tools that will support land managers to avoid or even remediate the negative processes of agricultural soil usage. A summary of core regenerative practices is provided in Table 8.2.

To sustain the resilience and health of the agroecosystem, there are many other practices which are known locally or globally as a regenerative practice

Table 8.2 Regenerative practices and their outcomes for the agroecosystem

Regenerative practice	*Outcome for agroecosystem*	*Example*
Zero tillage	Natural microbiome of the soil not disturbed (layers of aerobic and anaerobic taxa) Enhanced soil moisture	No-tillage significantly increased the relative abundance of *Acidobacteria*, whereas it decreased *Actinobacteria*, and had little effect on *Proteobacteria, Chloroflex*, *Firmicute*, and *Bacteroides*.[57]
Reduced tillage		30 years of reduced tillage in wheat monoculture resulted in greater field water capacity and available water content.[58]
Retention of crop residues	Constant supply of organic matter for the soil food web and C-sequestration	In a no-till wheat cropping system, rice residues enhance all the carbon pools (i.e. non-labile, less labile, labile, very labile, water-soluble and microbial biomass carbon) and glomalin content in the soil.[59]
Mulching	Preserves soil moisture	In varying edaphic and climatic conditions (137 studies of wheat monoculture), straw mulching in a no-till system significantly increased wheat yield, soil moisture and water use efficiency.[60]
Crop rotation	Reduction in pests and plant diseases in the agroecosystem Restoring the soil structure	Crop diversity increased disease-suppressive functional group *prnD* gene abundance within soil microbiome by about 9% compared to monoculture treatment.[61]
Cover crops	Shading of the soil surface resulted in e.g. counteracting moisture loss Stimulating soil enzymatic activity	White mustard had the most activating effect on the soil enzymes, particularly dehydrogenase and urease activity.[62]

(Table 8.3). In fact, RA is the agrotechnological basis for circular agriculture. Beyond processes for the production of biomass (Tables 8.2 and 8.3), there are many biological and thermal solutions for biomass processing in the circular economy, like composting, combustion, pyrolysis, hydrothermal carbonisation, incineration, gasification, anaerobic digestion and co-digestion, dry anaerobic digestion, vermicomposting, biorefineries, photobioreactors and various biosynthesis processes.[63]

Table 8.3 Other regenerative practices and their outcomes for the agroecosystem

Regenerative practice	*Outcome for agroecosystem*	*Example*
Pixel/*milpa*/*milpa push-pull* cropping	Enhancing three-dimensional biodiversity, land equivalent ratio and crop yields per area Eliminating of crossings on the field	A new regenerative practice *milpa push-pull* is proposed by merging the benefits of different companion plants for crop protection against pests, increased diversified yields, along with improved soil moisture, fertility and other benefits.[64]
Strip intercropping	Buffer strips with no tillage for soil beneficial organisms like earthworms	As compared with conventional tillage, the one-pass strip till system increased the stability of soil aggregates of 0.25–2.0 mm in diameter by an average of 12.7%, glomalin content by 0.08 $g \cdot kg^{-1}$ and weight of earthworms five-fold[65]
Other types of intercropping		Intercropping of Faba bean–barley in 2:1 alternate rows resulted in the highest dry matter, accumulated N yield and economic efficiency index of the plant mixture.[66]
Including perennial crops in rotation	C-sequestration Preventing degradation to soil structure	On 27 experimental sites, perennial cropped rotations increased SOC by 12.5%, corresponding to approximately 5.7 $Mg\ C \cdot ha^{-1}$ in the top 20 cm of soil compared to grain-only rotations.[67]
Crop diversification	Maintaining and enhancing the species, functional and genetic biodiversity of the plants while affecting the microbiome diversity structure	Increased the richness and diversity of soil bacteria genera in just one year of use of the intercropping system compared to 30-year maize monoculture[68]
Promotion of legumes	N-fixation in the legumes' rhizosphere, inoculation with *Bradyrhizobium* spp. and coinoculation with *Azospirillum brasilense* of the soybean crop in Brazil	Biological nitrogen fixation in soybean crops in Brazil[69]
	Alternatives to cereal–fallow rotation and cereal monoculture	High grain prices and valuable straw boosted profitability of farms in a Mediterranean-type climate; replacing fallow with vetch for hay production increased the average gross margin by US\$ 126 $ha^{-1}\ year^{-1}$.[70]

(*Continued*)

Table 8.3 (Continued)

Regenerative practice	*Outcome for agroecosystem*	*Example*
Soil bioadditives	Liming (addition of $CaCO_3$) improves soil aggregation, flocculation and porosity	Liming decreased bulk density in clayey soils even 12 months after application.[71]
	Reservoir of active substances to strengthen allelopathy relations and supply of organic matter to the soil system	5% biochar proportion in soil derived from maize straw with addition of 2 $mL\cdot g^{-1}$ of wastewater from molasses fermentation improved ryegrass growth, soil fertility and soil catalase activity.[72]
	Agricultural waste treatment technologies expand the range of fertiliser types	Biochar application in agriculture can yield positive outputs in both an environmental and circular economy context[73]
Ley farming	C-sequestration	Including perennial legume-grass leys as main crops in the half of crop rotation with maize accounted for 80% of the observed carbon sequestration in the topsoil.[74]
Agroforestry		The net carbon sequestration rate in poplar and eucalyptus was 10.3 and 12.7 Mg $C\cdot ha^{-1}\cdot yr^{-1}$, respectively.[75]
Integration of livestock into crop production systems	Supply of natural fertilisers like manure, which slowly release nutrients and steadily change soil pH	Goat manure promoted atrazine degradation in soil, via enhanced deethylatrazine and deisopropylatrazine pathways, by increasing soil pH and organic matter content, as well as the abundance of the *Nocardioides Sphingomonas* and *Massilia* taxa, in the soil.[76]

In Poland, a new framework – the Carpathian Quality System for Grass-Fed Beef (CQS-Beef) – has been proposed (Figure 8.6). In this system, meat production is based on agroecological principles (i.e. RA), contributing to the stability of mountain agrocenoses while preserving biodiversity, protecting water and soil, and mitigating climate change by reducing carbon footprint. At the same time, CQS-Beef diversifies agricultural production and results in an increase in profitability and in the attractiveness of mountain areas to tourists.

To intensify the outputs of regenerative practices in the field, precision agriculture tools are employed. Precision agriculture applications include a range of technologies such as global positioning systems, geographic information systems, sensors, drones and machine learning.[78] Precision agriculture can help farmers to manage irrigation, fertilisers, and pesticide use more effectively by spot application, based on real-time information on soil fertility and crop needs (Table 8.4). To sum up, there are a few organisations that provide farm RA

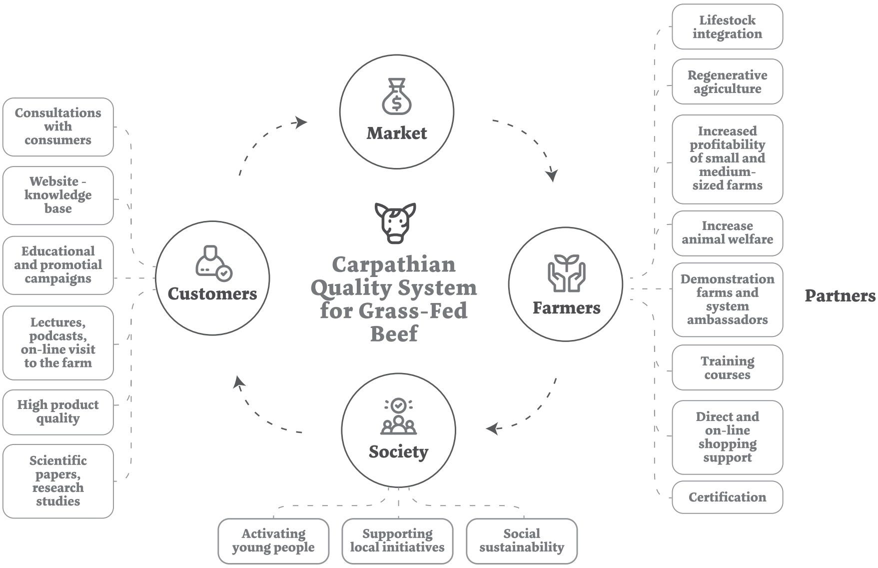

Figure 8.6 Carpathian quality system for grass-fed beef.[77]

Table 8.4 Precision agriculture tools and their outcomes for the agroecosystem

Element of precision agriculture	*Outcome for agroecosystem*	*Example*
Global positioning system	Creating precise maps of soil characteristics, topography and other features that affect crop growth	The real-time kinematic global positioning system generates accurate topographic maps of agricultural areas.[79]
Geographic information systems		A 4-graded drought-resistant soil map was created as a base map for drought management projects in Turkey.[80]
Sensors	Monitoring crop health, water use and pest infestations	TDR soil moisture sensors used to estimate evaporation intensity of an injection-irrigated soil.[81]
Drones		The indication of phosphorous and potassium deficiency in rye monoculture.[82]
Machine learning	Analysing vast amounts of collected data	Identification of microbial strains that can mitigate drought effects in soil.[83]

certification services, for example, the Rodale Institute, Terra Nostra, Ecocert, the Regenerative Organic Alliance, the Land Institute, and Control Union.

In summary, the concept of 'regenerative' agricultural practices has a more active connotation than that of 'sustainable' agricultural practices, which refers to practices that maintain the natural environment in a condition no worse than the existing one. Furthermore, regenerative practices, in addition to adopted sustainable practices (e.g. cover crops, prevent biodiversity-rich sites across rural and urban landscapes, crop rotation, zero-residues crop production, agroforestry), provide ecology-based solutions based on scientifically investigated relationships and indigenous knowledge. However, in many studies, the term 'sustainable' remains synonymous with 'regenerative', 'conservation' or even 'organic' agriculture. Similarly, in urban ecosystems, 'regenerative' refers to an approach to urban agriculture which seeks to convert urban green space into productive landscape for the production of food and fibre, rather than just strengthening ecosystem functions in the face of a strong anthropogenic impact (i.e. the 'sustainable' approach).[84] It should also be emphasised that knowledge about regenerative practices in agriculture is passed down from generation to generation in families or producer groups who cultivate the soil intelligently and with passion.[85] That was the case after the quinoa boom (2010–2014), when Bolivian farmers from Southern Altiplano converted a climax community (shrubs, cacti, grasses) to quinoa cultivation. Then, after cash crop cultivation was abandoned, the land started suffered from wind soil erosion since the native plants did not grow back readily. Thanks to local knowledge, species and ecotypes of wild plants were identified and could have stopped land and soil degradation until a new quinoa variety more adapted to the environment was available on the market.[86]

8.3.2 Zero-residue crop production

Organic agriculture aims to provide a conscientious alternative to conventional practices, prioritising environmental sustainability and public health. Nonetheless, organic production has certain disadvantages when compared to traditional agriculture like lower crop yields than those achieved through conventional methods and higher costs due to increased labour expenses.[87] These limitations have given rise to a novel sustainable agricultural management approach in Europe known as *zero-residue production*.[88]

One of the options for ensuring high-quality production while also protecting consumers from pesticide residues appears to be the system of zero-residue production. A number of growers and marketing organisations within the EU are transitioning to the technology of pesticide residue-free farming. At present, several agricultural companies across Europe are following this standard, which ensures that, within certified production, the level of any of the active substances does not exceed 0.01 mg/kg. In the Czech Republic, among the first enterprises to transition to a zero-residue production system are vegetable growers using hydroponic systems. Hydroponic production, as a highly intensive production system, typically relies on high inputs of agrochemicals (nutrition, plant protection). In recent years, even in this sophisticated cultivation method, there has been a growing discussion about ecologisation, where individual components are replaced with substances that have no negative impact on the ecosystem and health. What does zero-residue production actually mean? Essentially, it represents a higher level of integrated production, placing a strong emphasis on various agro-technical measures. This includes activities such as soil fertility restoration and understanding the relationship between the plant and substrate, choosing an appropriate irrigation system, determining the right dosage and timing, evaluating plant nutrition through transpiration measurements and leaf analysis, preventing excess nitrogen in plants, and adjusting nutrient doses to influence plant resistance. Disease and pest prevention is primarily addressed through biological control (insects, predatory mites, bacteria, fungi, viruses and the use of pheromones, etc.). However, this does not entail an absolute exclusion of conventional pesticides. In cases of necessity or in the early stages of the vegetation cycle, conventional plant protection products can be used, but it is essential to ensure that the product will exhibit a maximum residue level (MRL) below 0.01 mg/kg by the time of harvest, which is the legislative limit for infant food. If it happens that not all residual components are eliminated by the harvest date, the production is declared as standard (conventional) if it is not within the required limits. Therefore, it is necessary to conduct analyses of all possible pesticide residues in an accredited laboratory. Unlike organic farming, the use of mineral fertilisers is commonly employed in this system. It should be noted that pesticide residue-free residue farming will incur increased costs for biological and non-chemical plant protection, education and knowledge of responsible workers, consultation and analyses for maximum residue levels.[89]

8.3.3 Organic farming

Organic farming (OF) is a special trend in agricultural production that is gathering more and more momentum across the world (globally, an increase of 327% in the number of farms in 2020 compared to the base year of 2017), although its share in terms of the area of all agricultural lands is still negligible (almost 1.25%) (OurWorldInData-organic agricultural area, 2023). Based on Eurostat,[90] there is almost 10% of arable land under organic growing systems in the EU.

Organic production should be based on properly planned crop rotation, in order to preserve and improve soil fertility, coupled with appropriate selection of plant species and varieties, as well as animal species and breeds, that demonstrate natural resistance to diseases and high adaptability to local environmental conditions.[91] By following the rules of OF, two very important goals are achieved: environmental protection of the soil, water and landscape, and high quality of food.

In the bioeconomy, products of OF still remain confined to the basket of richer consumers due to higher production costs. It is linked with e.g. greater labour input and lower high-quality yields from agricultural areas. Therefore, the conjunction of OF with crop diversification practices is desirable in current agriculture. Such practices were known in the ancient world, like intercropping of maize with squash and bean (Mesoamerican *milpa*).[92] In Europe, the positive and negative coexistence of plant species was noticed e.g. by the ancient Romans, like Varro.[93] The intercropping mode puts crops on a higher yield trajectory contrasted to sole crops. Jensen et al.,[94] based on 22 different organic field experiments with cereals (durum and soft wheat, spring barley) and grain legumes (faba bean, pea) at 13 locations in France and Denmark, concluded that 91% of the experiments resulted in greater total grain yields of cereal and grain legume intercrop than the mean sole crop yield. Mean yield of intercrop was equal to 3.3 $\mathrm{Mg \cdot ha^{-1}}$ as opposed to a sole crop yield of 2.7 $\mathrm{Mg \cdot ha^{-1}}$. The authors explain that the reasons for this state are to be found in agroecology, namely: reduction of nitrate leaching losses through more efficient use of soil mineral N by cereals and a more balanced C:N ratio of crop residues compared to sole crops, which contributes to a more balanced mineralisation–immobilisation turnover of N.

Today, this trend of intercropping has been combined with precision farming and returned to the mainstream as a *pixel cropping*, a method of growing different plants together at the same time on one patch of field (i.e. one pixel = a small plot of 0.25–2.25 $\mathrm{m^2}$ arranged in a grid).[95] Precision agriculture naturally fits into the management of such a field, because from sowing to harvesting specialised field tools (pixel cropping robots) accompany this highly diversified cropping system.[96]

8.3.4 Vertical farming and aquaponics

Growing in enclosed spaces offers numerous opportunities for applying the principles of the circular economy and efficient resource utilisation. From this perspective, greenhouse farms have the potential for high productivity with reduced water and agrochemical consumption per unit of production. They have a production capacity up to 10–15 times higher than that of traditional soil-based farming and also hold significant potential for water and nutrient recycling.

An innovative solution proposed to tackle sustainability concerns and meet rising food demand is the creation and operation of vertical farms. Vertical farming offers a multitude of advantages that are explained in Chapter 10.

Aquaponics is an ecologically friendly method of producing aquatic organisms (fish) and plants (Figure 8.7). This technology uses microbial transformations of aquaculture waste to provide nutrients for plant growth; at the same time, the plants serve as a filter to purify water for aquaculture. In an aquaponics system, neither pesticides nor herbicides are used and the total amount of water and fertiliser used is limited. Such a system also reduces the release of aquaculture waste into the environment. This closed-loop ecosystem is particularly efficient in water usage, making it an attractive solution in regions facing water scarcity. Additionally, aquaponics can be implemented in controlled

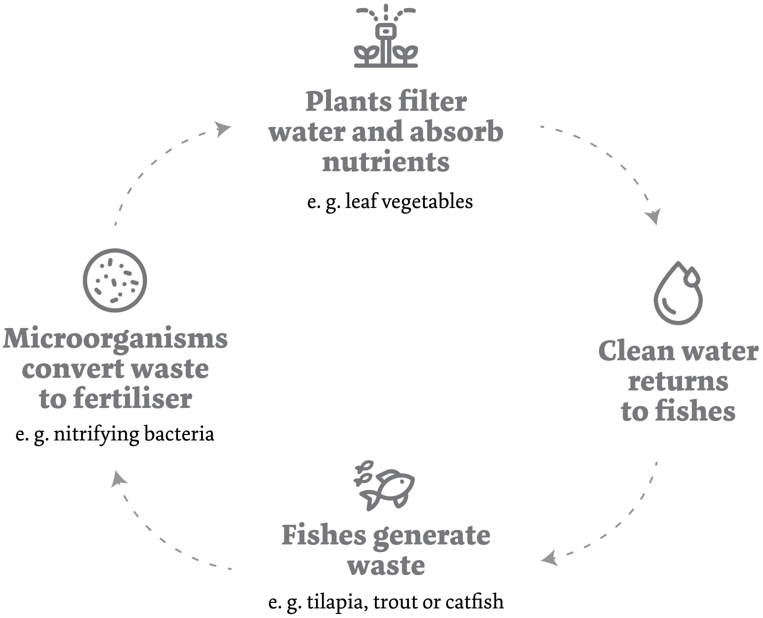

Figure 8.7 The various components and interactions within an aquaponic system.

urban environments, overcoming land limitations caused by urbanisation. To successfully operate an aquaponic system, various factors such as system design, water pH control, aeration, nutrient management and appropriate pairing of plant and fish species need to be considered. Aquaponics involves multiple disciplines, including aquaculture, microbiology, ecology, horticulture, agriculture, chemistry and engineering.[97] When comparing fish to meat as a source of protein, fish are commonly acknowledged to be an exceptionally healthy protein source. In the context of global food production, aquaculture currently supplies a greater amount of fish protein than traditional fishing.[98] Aquaponics therefore shows great promise as a technology capable of producing top-quality fish protein and vegetables with significantly reduced land, energy and water requirements. Moreover, it minimises the use of chemicals and fertilisers typically employed in conventional food production.[99] From a social standpoint, the aquaponic system enhances access to safe, locally cultivated agricultural products. Aquaponic systems entail a substantial initial investment for integrating two productive systems. However, once established, they incur lower management costs and generate combined returns from both fish and vegetable sales.[100]

8.3.5 Use of bioadditives

In some countries, the use of fertilisers on agricultural land leads to serious issues related to the accumulation of residues in food chains and contamination of groundwater.[101] It has been stated that increasing costs of chemical

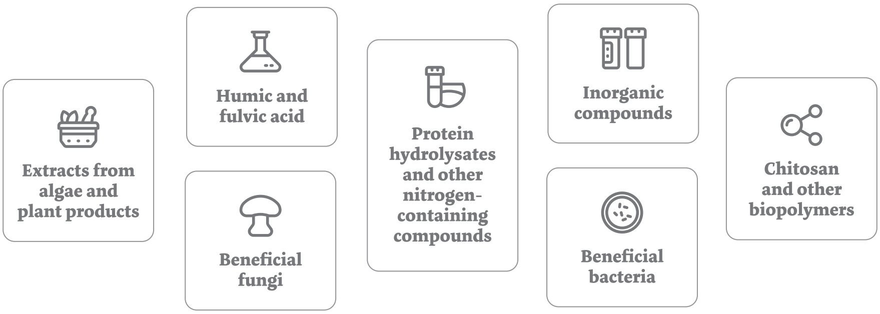

Figure 8.8 Plant biostimulants and main categories.

(based on du Jardin, 2015).[106]

fertiliser use and massive inputs of non-renewable resources will lead to greater efforts being put into researching alternative preparations.[102] According to Van Oosten et al.,[103] biostimulants can contribute to more sustainable and resilient agriculture, offering an alternative to synthetic preparations increasingly viewed as unacceptable by consumers.

The term *plant biostimulants* currently refers to any substance or microorganism applied to plants to increase nutrition efficiency and resistance to abiotic stress, or to improve production quality, regardless of nutrient content[104] (Figure 8.8). A broader definition by Halpern et al.[105] characterises plant biostimulants as substances or materials, excluding nutrients and pesticides, that, when applied to plants, seeds, or growing substrates, have, in certain formulations, the ability to modify physiological processes in plants in a way that provides a potential benefit for growth, development or stress responses. For a long while, the EU lacked a definition of biostimulants in legislation. Since 2022, there has been a new EU Regulation 2019/1009 (2019) determining that a

> *plant biostimulant [is a] product the function of which is to stimulate plant nutrition processes independently of the product's nutrient content with the sole aim of improving one or more of the following characteristics of the plant or the plant rhizosphere: (a) nutrient use efficiency, (b) tolerance to abiotic stress, (c) quality traits, or (d) availability of confined nutrients in the soil or rhizosphere.*

Considering that biostimulants are derived from an incredibly diverse group of biological and inorganic materials,[107] including products of fermentation of plant and animal products, live microbial cultures, macro- and microalgae, protein hydrolysates, humic and fulvic acids, composts, manure, industrial waste, and food industry by-products created using significantly different production processes, it is illogical to assume that there is a single mode of action for biostimulants.[108] Due to their diversity and complexity, precise mechanisms of action for biostimulants are difficult to determine. Nevertheless, some important pathways have been defined by Posmyk and Szafrańska.[109] To sum up, an ideal biostimulator should have the following characteristics. It has to be: (i) non-toxic, safe for animals and environment; (ii) easily and actively taken up by plants from environment; (iii) of natural origin or easily synthesised in laboratories; (iv) not expensive; (v) dissolved in different solvents: water, alcohols but also lipids – that facilitates the use of various application methods; (vi) easily penetrating cell compartments; and finally, (vii) it must improve plant resistance to adverse conditions and help generate tolerance to stresses.

Biostimulants can have an effect on soil conditions or can directly influence plant physiology.[110] Depending on their composition and desired results, they can be applied to soil or leaves. However, the influence of biostimulants on plants may vary both between plant species and even between cultivars, depending on environmental factors, application dose and timing.[111] A significant group of biostimulants includes microbial preparations (fungi, bacteria, algae). According to the findings of Kopta et al.,[112] it was possible to conclude that the combination of selected bacteria and freshwater algae may be a suitable way to positively influence plant yields, especially under stressful conditions. Based on Saha,[113] the biostimulants industry is expected to develop at a pace of about 10% annually. According to the European Biostimulants Industry Council,[114] the European biostimulants industry is well-positioned on the international scene since it represents over half of the worldwide market. Estimates of the value of the European market in 2022 range from US$1.5 to 2 billion. According to an October 2023 update from the Czech Republic's public fertiliser register,[115] there are a total of 1,002 registered preparations falling under the category of "Plant biostimulant".

8.3.6 Plants for the bioeconomy: Neglected and underutilised plants

To strengthen the bioeconomy from the agriculture side much more public and academic debate is needed to rediscover niche edible plants (*neglected plants*), whose cultivation has been abandoned in various regions of the world. Rapoport and Drausal[116] estimates that, of the 270,000 plant species recognised in the world, about 27,000 should be edible for humans. Two years later, a book entitled *The nature of crops* by John Warren[117] was launched. In it, the author indicated there to be more than 400,000 plant species worldwide, of which 300,000 are quite possibly edible (today, people usually consume only about 200 plant species, among which rice, wheat, corn and soybean are the most frequently cultivated and consumed plants). Regardless of the exact number of species, the disproportion remains the same and as-yet unappreciated, uncultivated plant species could play a strong part in these bioeconomies and the communities that will discover them and will be able to adapt them to their socioeconomic conditions. Many of these plants are species that adapt quite well to the environment, so the limiting factor here lies in consumer preferences and the development of demand on the demand side of the economy.

Cultivation of wild or native neglected plants is also one of the regenerative practices in agriculture that can increase the diversity of crop species in agricultural areas. This also plays a part in designing a bioeconomy that is more resistant to crises from outside factors. An example of such a plant is *Linum lewisii* (Linaceae family), which originates in western North America. This is one of the plants to be explored in the future as an oilseed crop growing in dry, oligotrophic agroecosystems.[118] Another example is seabuckthorn (*Hippophae rhamnoides*),[119] which could serve as a multifunctional plant in both an environmental context (to prevent soil erosion and as a probable enhancer of biodiversity of post-mining[120] or natural landscapes[121]) and a social context (as a plant with health benefits[122]). Another neglected plants now being (re-)discovered include sweet clover, a legume of the genus *Melilotus* sp.,[123] which has been successfully incorporated as a cover crop either used alone or in a mixture with barley, causing e.g. an increase in the population of soil bacteria in wheat cultivation, especially affecting the *Archea* group.[124]

Although identifying neglected plants is relatively simple, getting the information to end-consumers, encouraging them to change their food preferences and organising an efficient food supply chain are all bottlenecks in bioeconomies. Some attempts are being made in certain regions to cope with that problem at an academic[125] or public level.[126]

*8.3.7 Future plants for the bioeconomy: a multifunctional plant – Topinambur (*Helianthus tuberosus *L.)*

The Jerusalem artichoke (topinambur, *Helianthus tuberosus* L.) is a perennial root plant that originated from the north-eastern region of what is now the United States of America and was brought to France between 1609 and 1617.[127] Over the centuries, it expanded its area of occurrence in Europe and served both as an edible (i.e. tuber) and an ornamental plant. Due to their reserve in the substance inulin (in contrast to the starch e.g. in potatoes), Jerusalem artichoke tubers are recommended as part of a diet for diabetics and patients during post-cancer recovery.[128] Inulin-like substances are also responsible for the frost-resistant feature of tubers (they remain viable after frost up to −30 °C) and are an easily hydrolysable material[129] for sophisticated alcoholic beverages,[130] as well as a raw material for energy sector (bioethanol and biofuel production). Since the underground and aboveground parts of the plant develop considerable biomass[131] and have fair energy potential,[132] this plant is considered for use in next-generation biofuel production systems.[133] The positive potential of topinambur in land remediation processes has been noted by Antonkiewicz and Jasiewicz[134] with regard to heavy metals like Cd and Zn. Zhang et al.[135] indicated this genus as a salt stress tolerant. The cultivation of topinambur in forest settings could help to stop crop damage caused by wild animals,[136] which are problematic and generate wide-scale, unpredictable costs for bioeconomies. *Chaff* from the raw stems is a good substrate medium for the production of edible mushrooms,[137] or in industrial processes for use with laboratory microorganism cultures.[138]

The abovementioned features of this plant, coupled with the technological progress in the processing of its biomass, result in there being many applications of different parts of its biomass to meet the needs of current bioeconomies. However, this plant species is also recognised as an invasive taxon in ecosystems[139] due to the high viability of even a small part of the tuber or rhizome left in the soil. Thus, this feature must also be taken into account as a hidden cost of the cultivation this plant.

Bioeconomy is not an autonomous sector of the economy, but rather a complex of relationships involving agriculture, industry, biotechnology, service sectors and consumers[140] (Figure 8.9).

The agricultural sector plays a pivotal role in strengthening or weakening the whole structure of the bioeconomy since it crucial for food safety and has a direct impact on the quality of the natural environment. On one hand, the Food and Agriculture Organization (FAO) underscores that nearly 95% of our food is reliant on soil for production. On the other hand, food production is responsible for approximately 25% of the world's greenhouse gas emissions.[141] There are many attempts around the world to make agriculture more rooted in ecology science in order to more efficiently manage the natural goods of bioeconomies. Many of them, like regenerative agriculture, permaculture or vertical farming, are proposed by some as approaches based on a semi-closed holistic system designed to reduce or eliminate dependence on external (e.g. synthetic) inputs, which also directs the bioeconomy towards a circular bioeconomy.[142] As Ray et al. mentioned, we still have a huge undiscovered potential of "*thousands of edible species remained wild or semi-wild, and were left out in the course of domestication; however, these underutilized edible floral elements hold the potential to transform our food systems toward being more nutritious, sustainable, and resilient to climate change*".[143] It is noteworthy to mention that there is no need to reject monocultural cultivation as a viable practice for the bioeconomy, provided that the environmental impact is mitigated through practices such as adapting crop fields to be more conducive to wildlife, restricting the use

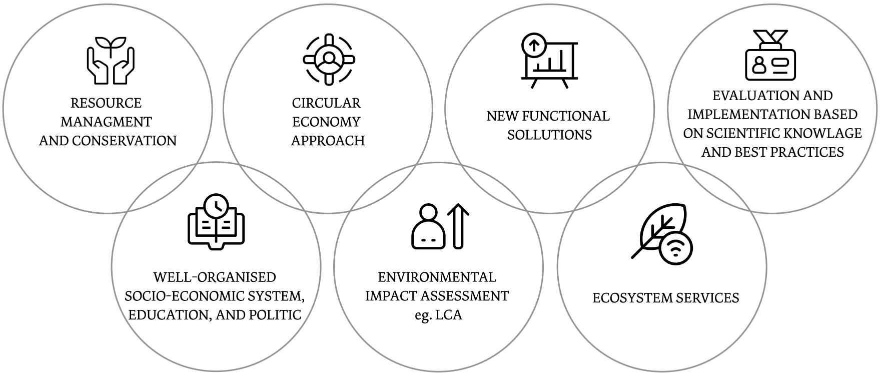

Figure 8.9 A framework for an environmentally safe bioeconomy.

of harmful pesticides, implementing measures from organic and regenerative farming, and utilising bioadditives and other strategies outlined in this chapter. Organic farming coupled with intercropping practices provides outcomes through diversity-mediated mechanisms, both in terms of yield and ecosystem services for the bioeconomy.

Notes

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Part III

Closed circuit

Production, processing and fertiliser

9 Production for the bioeconomy

Sustainable primary and secondary production of bio-based resources

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9.1 Introduction

In the past, during the Neolithic period, most areas of the world were covered by natural wildernesses, consisting mostly of forests, meadows and steppes. This state of equilibrium lasted for the next 1,000 years, during which period, according to estimates, only 4% of the world's surface area was used for agricultural purposes. Unfortunately, with the growth of the human population, wild habitats have largely been replaced by agricultural land, which have been, and continue to be, mainly perceived as a source of biomass used for two main purposes: producing human food and animal feed and generating energy. According to Doughty and Field,[1] humans currently use or alter the productivity of between 23 to 40% of global terrestrial net primary production (NPP) (15.6 Pg C yr^{-1}), of which 53% is harvested, 40% is from land-use-induced productivity changes, and 7% is from human-induced fires.[2] Globally, humans harvest 8 Pg C yr^{-1} of NPP (50% of this is for crops, 29% is for pastures, 11% is for forestry, 6% is for fires, and 4% is for infrastructure).

According to Doughty and Field,[3] in 800 AD, the world population was approximately 220 million, and liberated NPP had been utilised in parts of Europe, India and China where populations were concentrated. By 1850 AD, global populations had increased to ~1.2 billion, and liberated NPP had been appropriated in much of Eurasia and Africa, but was still available in much of Australia, South America, and western North America. Today, liberated NPP has been appropriated in most of the world and NPP usage through agriculture vastly exceeds that which had been consumed by the mega-herbivores. Humans have exceeded this NPP usage by replacing natural ecosystems with agro-ecosystems that are often subsidised by irrigation and fossil fuel energy sources.[4]

The Neolithic agricultural revolution is considered to be one of the most important events in human history. The agro-transformation observed throughout history has been the result of meeting the subsistence needs of humanity. This led to the domestication in the Middle East of wheat (in around 9,000 BC), peas (in around 8,000 BC) and lentils (in around 5,000 BC), and the domestication of maize and beans in Central America. Similarly, South

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Americans domesticated the potato, and rice and millet were domesticated in China[5] (Harari, 2015). The next step in the process of agro-transformation was to increase the productivity of domesticated crops by interfering with the natural environment (nature), to cover the subsistence needs of a growing population for food and energy. This process took place over thousands of years, and resulted in a significant increase in the primary production of biomass to meet the subsistence needs of a growing global human population. The development of industrialised agriculture as an effect of the Industrial Revolution in the 19th century was an important turning point (Figure 9.1).

During the period of industrialised agriculture, there was a significant increase in crop productivity thanks to the introduction of mechanisation and chemicalisation on a broad scale and to progress in biology. This was linked to an increase in demand for energy obtained from fossil fuel sources but also from biomass. The industrialisation of agriculture guaranteed growth in net primary production at the expense of degradation to the agricultural and natural environment. This was described by the World Commission on Environment and Development in the Brundtland Report 'Our Common Future', published in 1987. A new 'post-industrial' revolution, which is currently taking place, is forcing changes not only in the management of primary and secondary biomass, but also in the protection of natural resources. A key element of the post-industrial revolution is a change in approach to

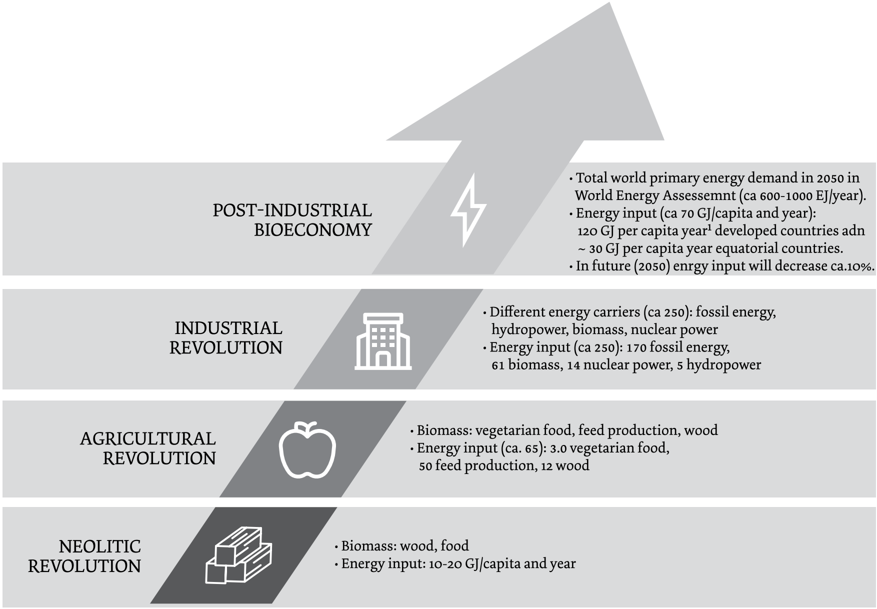


Figure 9.1 The bioeconomy as an element in agro-transformation.

Source: Adapted from WBGU[6] and Birner[7].

production and consumption, and the circular bioeconomy as a catalyst of systemic changes encompassing all sectors of basic production, which use and produce biological resources and all economic and industrial sectors, which use biological resources and processes for the production of food, animal feed, energy and services.

9.2 Primary production[8]

Primary (or basic) production can be understood as matter produced by autotrophs, in other words producers. In the case of plants, or photoautotrophs, it is understood as the accumulation of energy from solar radiation transformed via the process of photosynthesis into the chemical energy of bonds in the organic compounds from which plant tissues are composed. To keep things simple, in the context of this book, it shall be used to refer above all to the cultivation of plants. However, on the ecosystem level, primary production (PP) can be quantified by the following common metrics: gross primary production (GPP), net primary production (NPP), and net community production (NCP).[9] GPP measures community-wide photosynthesis, representing the total production of organic carbon or O_2 by autotrophs (e.g. phytoplankton, cyanobacteria) and represents the photosynthetic energy availability to the entire food web. GPP is reported as gross oxygen production (GOP) or gross carbon production (GCP), when defined in O_2 or carbon equivalents, respectively. NPP refers to the net production of autotroph biomass when accounting for autotrophic respiration (i.e. organic matter oxidation; AR), and represents the amount of photosynthetically produced organic carbon available to heterotrophs (e.g. bacteria, zooplankton, fish). Lastly, NCP is the difference between GPP and respiration by autotrophs and heterotrophs (i.e. community respiration – CR), and therefore determines if an ocean region is net autotrophic (net production, indicated by NCP > 0) or net heterotrophic (net consumption and NCP < 0).[10] When measured over sufficiently large temporal and spatial scales, NCP quantifies the amount of photosynthetically produced organic matter that sinks from the upper ocean (Laws, 1991). All PP fractions are often expressed as volumetric equivalents of organic carbon or O_2 production (e.g. mol C or O_2 m^{-3} d^{-1}), such that respiration has negative values.[11]

Primary production is a main source of biomass; therefore, it occupies a key place in the circular bioeconomy. The global production of primary crops reached ca 9.5 billion tonnes in 2023[12] (Faostat, 2023). Cereals consists the main source of biomass, followed by sugar crops, vegetables and oil crops (Table 9.1). The biggest producer of wheat is Asia, while the biggest producer of maize is America. Europe concentrates mostly on cereals production, which is the most important source of biomass use for different purposes. Most of the uses of biomass are for food production. Animal feed and bedding accounts for almost 40% (393.0 Mtdm, net of exports of animal-based food products) and plant-based food accounts for 9.7% (95.7 Mtdm). With respect to

Table 9.1 World production (thousand tonnes) of primary commodities crops[14]

Country	*Total*	*Wheat*	*Maize*	*Sugar cane*	*Rice, paddy*	*Potatoes*	*Oil palm fruit*
World	9 489 900	770 877	1 210 235	1 859 390	787 294	376 120	416 397
Africa	988 684	29 219	96 637	94 282	37 189	28 099	23 137
America	2 514 371	99 666	592 356	961 894	37 735	46 151	23 974
Asia	4 753 420	340 462	378 856	770 306	708 148	197 536	365 965
Europe	1 115 582	269 184	141 848	-	3 784	102 508	-

Source: FAO. 2023.[15]

non-food products, materials account for 28% (276.4 Mtdm) and energy for 22% (216.9 Mtdm). Total agricultural biomass production is estimated by differentiating two main components: *Economic production* – primary products, i.e. grains, fruits, roots, tubers; and *Residue production* – secondary products, i.e. leaves, stems and husks.

The assessment of agricultural biomass includes the major crops cultivated in Europe, grouped in nine main categories: cereals, sugar and starchy crops, oil-bearing crops, plants harvested green, permanent crops, vegetables, pulses, industrial crops and energy crops. The most important category are cereals and oilseeds crops, which are the most desirable for the food, feed and industrial market.[13]

According to JRC,[16] the total supply of biomass, which includes domestic production and net import, from primary productions systems (i.e. not including waste or by-products streams) in the EU-27 adds up to approximately 1 billion tdm and uses amount to 1.2 billion tdm. Almost 90% of this biomass is produced in the EU-27, while 5% of the biomass supply is imported from extra-EU countries (the origin of the remaining 5% is unknown). Of the total biomass available for further processing or consumption, approximately 70% is of agricultural origin, making agriculture the largest source of harvested biomass in the EU-27. Woody biomass accounts for 25% of the total. The relative weight of the fisheries and aquaculture sector is quantitatively quite small (<1%). Agricultural crops account for 50% of the biomass produced in the EU, and their collected residues account for 9%, with forestry accounting for ca. 27% (Figure 9.2). The trend in the supply of biomass from waste recovery is an increasing one. Most of the uses of biomass are for food production. Arable biomass from agriculture production is mainly used as feed and bedding (ca. 55%). Non-food products (ca. 45%) include: bioenergy (22%), materials – including biofuels (12%) and plant-based food (11%). In order to decrease pressure on the environment, more efforts should be put into improving the utilisation of biomass in different sectors of the bioeconomy. The EU uses biomass to meet its needs for food, feed, energy and materials (Figure 9.2). A considerable portion of the agricultural biomass produced by EU is used for feed, which is related to increasing demand for secondary production.

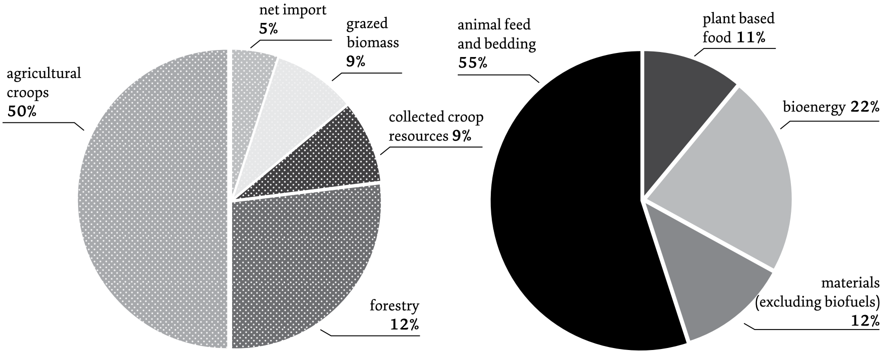


Figure 9.2 The total supply (a) and used (b) of primary productions systems (based on JRC, 2023).[17]

In order to meet the demand of the growing world population, food production should increase by 60%. This goal will be achieved if sustainable primary and secondary production of bio-based resources will be developed together in the same strength.

9.3 Secondary production

In this chapter, we are going to understand secondary production as the creation of a living mass of a heterotrophic (and thus foreign) population or group of populations over a certain period of time.

According to Food and Agriculture Organization of the United Nations (FAO) data, livestock account for almost 40% of total agricultural production in developed countries and about 20% in developing countries, supporting the livelihoods of at least 1.3 billion people around the world and providing about 34% of global food protein.[18] Currently, the greatest demand for animal products is recorded in Asia, which is clearly related to the size of the population in this region of the world. However, the biggest progress in meat production is noticed in Africa (Table 9.2.a). Feeding the world in 2050 by offering the global population a healthy, balanced diet and respecting the environment is a huge challenge. Recent data indicate that over the past few years (2020–2023), there has been a global trend towards increased beef production and consumption, mainly in Brazil, China and Canada (Table 9.2.b). Unfortunately, this meat production is considered as unsustainable in many regions of the world, with negative environmental impacts. Only in Europe is there a slight decline in pork production (since 2022) due to the active promotion of sustainable, low-carbon livestock production, involving increases in animal welfare and a reduction in antibiotic use. According to Peyraud and MacLeod,[19] the sustainability of livestock can be improved by more fundamental redesign of agricultural systems involving shifts from linear approaches to circular approaches. The inclusion of a wider perimeter considering livestock farming as one

Table 9.2.a Global meat production and growth

Region	*Production (kt cwe)*		*Growth (%)*	
	Average 2020–2022	*2032*	*Average 2020–2022*	*2032*
World	340 775	382 080	1.34	0.95
North America	52 927	55 780	2.03	0.44
Latin America	55 817	63 302	1.63	1.16
Europe	64 378	63 119	1.40	−0.01
Africa	17 979	22 570	1.86	2.30
Asia	143 372	170 404	0.97	1.26
Oceania	6 301	6 905	−0.33	0.72
Developed countries	134 623	138 461	1.58	0.32
Developing countries	206 152	243 619	1.19	1.33

Source: OECD/FAO (2023).[20]

Table 9.2.b Pork production and consumption – selected countries

Region	*Unit (1,000 Metric Tons)*	*2020*	*2021*	*2022*	*2023*	*2024*(Jan.)*
Brazil	Production	4.125	4.365	4.350	4.600	4.675
	Consumption	2.949	3.047	3.033	3.152	3.177
Canada	Production	2.115	2.101	2.082	2.050	2.015
	Consumption	856	858	911	1.000	995
China	Production	36.34	47.5	55.4	56.5	55.2
	Consumption	41.52	51.72	57.43	58.68	57.34
European Union	Production	23.21	23.61	22.28	21.50	20.70
	Consumption	18.20	18.72	18.22	18.40	17.70
Total	Production	96.08	107.95	114.53	115.49	114.15
	Consumption	95.25	107.24	113.23	115.00	113.75

Source: United States Department of Agriculture Foreign Agricultural Service, 12 January 2024.
*Estimation for 2024.

element of a circular agri-food system within planetary boundaries opens new prospects for progress in addition to tracks already explored. Those tracks concern rethinking of progress (husbandry and genetics practices) in the livestock farming system, rethinking the links between livestock farming and plant production and also the links between livestock production, food processing and consumption.

There is expected to be a 15% increase in demand for animal products (mainly meat) over the next ten years, and global consumption of milk and dairy products is forecast to grow by 25% between now and 2027.[21] Products of animal origin are still considered to provide humans with key nutrients (much more than just protein) that are not available from plants due to lower content in (or lack of) such nutrients, lower bioavailability and/or the presence of antinutritional factors. Globally, only 14% of the dry matter consumed by farm animals is edible for humans. Animals are very useful for transforming the remaining 86% (grass and crop residue) of inedible biomass into highly nutritious food for humans and manure, which is a source of nutrients and carbon for plants and soils. This is, in principle, a closed loop.[22]

Livestock farming allow food production on 57% of land which cannot be used for crops (marginal land), providing ecosystem services.[23] Livestock production, especially in the case of herbivorous animals, contributes to food safety by making it possible to valorise grazed marginal lands that are cannot be used to produce food crops directly for human consumption. Worldwide, 360 million cattle and 600 million small ruminants provide 25% of the world's livestock product from marginal lands.[24]

There are significant differences in the impact that animal production has on the environment. Extensive systems of production use less inputs, such as feed, energy and water, suggesting a lower impact on the environment. However, such an approach is considered to be inefficient compared to intensive animal farming from the point of view of resource use, taking the low level of production into account According to Adesogan et al.,[25] intensive animal farming does nevertheless lead to degradation of the natural environment. Grzinić et al.[26] noticed that intensive poultry farming leads to emissions that impact various environmental compartments, including air, water and soil. According to Dróżdż et al.,[27] poultry production, manure use and storage are linked to ammonia (NH_3), nitrous oxide (N_2O) and methane (CH_4) emissions, and therefore have an impact on greenhouse gas emissions as well as animal and human health. Baker et al.[28] pointed out that ammonia emission factors are subject to considerable variability and uncertainty. In a study of US farms it ranged from 0.035 kg to 0.789 kg y^{-1} per bird. Assuming a NH_3 deposition velocity of 2.4 cm s^{-1}, the estimated total annual ammonia deposition is 11,100 Mg y^{-1} (95.5% on land and 4.5% on water).

Improving the structure of the animal population so as to increase productivity would make it possible to limit the consequences for the overall population and thereby reduce greenhouse gas emissions. At the same time, to ensure the ongoing sustainable development of land on which it would not be possible to keep livestock with high productivity due to the lower quality of soil or also limited possibilities to grow feed crops, breeding animals with lower productivity would be justified if they would make use of permanent grasslands, thus helping to increase productivity of plant biomass from those lands and an increase in the sequestration of carbon from the atmosphere. In the technologically advanced breeding systems where high-productivity animals are kept, there is the additional possibility of limiting greenhouse gas emissions with food additives for ruminants and the use of excrement for the production of biogas (Danish model) as appropriate.

9.3.1 Use of red biomass and products of animal origin as an opportunity for development of sectors of the bioeconomy

The breeding of livestock has many benefits. The most important of these is covering the need for animal protein. However, it is a part of production during which it is important to manage waste both in the process of the growth and development of animals and also in relation to the slaughter and the processing of red biomass. The role of the bioeconomy is to raise people's awareness of the possibility of making use of this potential and thus increasing its use in practice.

The development of the bioeconomy is related not only to the use of primary production but also of products obtained from secondary production.[29] The management of waste red biomass is a serious challenge and requires appropriate organisation of entities of the meat industry, paying attention to the application of sanitary and environmental standards.[30,31] Thanks to thermal utilisation, plants that neutralise waste from the meat industry become producers of energy that can be used, amongst other things, for heating and the production of domestic hot water.

In the slaughter process, apart from the edible parts of the carcass, other products are obtained which constitute valuable secondary raw materials. These products are collected after slaughter. The raw materials obtained are a source of leather used in the production of shoes, clothes, upholstery for cars and furniture, and many other accessories. In the slaughter process, animal endocrine glands are also obtained and used in the production of modern medicines of the highest quality for humans.[32,33] Medicinal products that can be produced from animal glands include epinephrine, oestrogens, progesterone, insulin, trypsin, parathyroid hormone, adrenocorticotropic hormone (ACTH), somatotropin, thyroid-stimulating hormone, testosterone and thyroxine.[34] Blood is also a valuable by-product. As a liquid tissue containing a mixture of a cellular fraction and plasma (red blood cells, white blood cells and platelets), it accounts for around 4% of live animal weight.[35,36] It is rich in iron, proteins and bioactive compounds, which are suitable for consumption by humans and farm animals.[37] In the food industry, blood is used as a binding agent, colour enhancer, emulsifier, fat substitute and meat curing agent.[38] In medicine and microbiology, processed blood is used as a medium for the growth of probiotic bacteria (bovine plasma), raw materials for the production of a pharmaceutical porphyrin derivative.[39] Products obtained from the poultry industry consist mainly of feathers, which are typically used for the stuffing of mattresses and pillows, as well as feather dusters, and are also used for the production of innovative biodegradable, composite non-wovens with barrier properties.[40]

Case study

Development of innovative protective non-wovens with the addition of feathers

Within the framework of a scientific project conducted by partners, including the University of Agriculture in Kraków, an innovative technology for the production protective non-wovens with the addition of feathers was developed. The aim of the project was to develop methods of management of waste in the form of feathers. Within the framework of the project, it was envisaged to develop guidelines for the deployment of the production of two groups of composite non-wovens with the addition of waste feathers from poultry abattoirs: protective non-wovens for covering snow piles and protective non-wovens for covering new sowings of grass-bean mixture (which is used in difficult areas such as: slopes, embankments, newly formed ski slopes). The proposed solutions are environmentally friendly and safe for human health, while at the same time ensuring a reduction in biomass waste in the form of feathers, accumulating in and polluting the environment. Actions taken as part of the project are conducive to protection of the ecosystem and its revitalisation. The beneficial impact of the new and innovative protective non-wovens on the biological activity of soil also contributes to the development of biodiversity, in line with the idea of the European Union Directive on soil protection of 15 November 2007.

In addition, feathers are also one of the most complex coating structures, containing keratin proteins widely used in the cosmetics industry (Table 9.3). There are also indications that microorganisms which degrade feathers into feed for poultry may also be used for the production of biogas.[41] Moreover, it has been shown that the use of heat and steam under high pressure hydrolyses feathers into a useful, cysteine-rich, high-protein product that is 60% digestible.[42] These degraded feathers can be used for the production of fertilisers due to their high protein and nitrogen content.[43] In addition, chicken feathers can also be used for the production of strong thermoplastics (such as polyethylene nylon, polyvinyl chloride and polystyrene) after chemical processing into methyl acrylate.[44] Such use of biomass is an example of the practical implementation of the principles of sustainable development of the bioeconomy.[45]

Table 9.3 Multidirectional use of red biomass and other products of animal origin based on the example of the poultry industry

Industry	*Product*	*Application*
Poultry industry	Feathers	Mattresses, pillows, biodegradable non-wovens[46] Production of biogas[47] Production of fertilisers[48]
	Keratin proteins obtained from feathers	Cosmetics[49]
	Liver extracts	Medicines[50]

Animal production, especially in relation to cattle, should be limited for environmental reasons. However, only assuming that full potential is made of the opportunities in different sectors of the bioeconomy. In order to limit the production of red biomass, sustainable development goals should be pursued, which take the economic, environmental and social dimensions of production into account.

9.4 Sustainable agriculture system as a source of primary and secondary production

Sustainable agriculture means integrating crop and animal production to meet the nutritional needs of a growing global population while protecting the environment. This system guarantees high efficiency of crop production and/or livestock breeding making optimal use of non-renewable resources on the farm, integrates natural biological cycles, and ensures the farm remains economically profitable. One important aspect of sustainable agriculture is the improvement of all practices and processes, which add value to primary production by making use of efficient technology and available knowledge and taking consumer preferences into account. In the sustainable agriculture system, innovative practices are used in crop cultivation in order to increase the production of biomass, including the creation of new varieties, multi-species mixed sowing of plants, use of bio/photo-stimulators, living and/or biodegradable mulches, application of biochar obtained from biomass, and precision fertilisation (Table 9.4). Thanks to innovative technological solutions, it is now possible to obtain green biomass of high quality with a minimal burden on the environment. Varieties of the new generation of utility crops, including wheat, sugarcane and maize, which are more productive (production of raw material), and therefore more useful for society (case study), are an example of this.

Currently, agriculture is faced with new technological challenges related to the production of the high-quality biomass needed for nutritional and industrial purposes. The introduction onto the market of new technologies for the production of biomass has two goals. The first and overriding goal of the technologies introduced is to increase the profitability of the production of biomass, while the second goal is to increase its efficiency, while protecting the environment. This is why it even more crucial to integrate farming systems so that they take both economic and environmental aspects into account. One of the leading environmental management techniques is the technique of Life Cycle Assessment (LCA), which assesses farming systems and technologies, and helps with designing new ones based on environmental services.

Table 9.4 Sustainable practice for enhancing biomass quantity

Sustainable practice	*Crops*	*Biomass yield ($t\ ha^{-1}$)*
Intercropping of cereals in mixture	Winter cereal mixture with hybrids	Rye and triticale mixture (12 t ha^{-1} of seed yield) Hybrid rye in pure stand (11.5 t ha^{-1})[51]
Crop production in leaving mulch or biodegradable film system	Wheat + living mulch	5.5–6.3 t ha^{-1} [52]
	Maize + living mulch	13.5 t ha^{-1} [53]
	Soybean + biodegradable film	3.8 t ha^{-1} [54]
Crop production with biostimulators	Potato	Dry mass of potato tubers: 9 – 12 t ha^{-1} [55]
	Winter rape	4.16 t ha^{-1} [56]
Crop production with biochar from sunflower husk	Soybean	3.8 t ha^{-1} [57]
Precision fertilisation	Maize	9.0 t ha^{-1} [58]
Crop production with struvite based from wastewater	*Festuca arundinacea*	Pot experiment: After 180 days dry matter reached 6.63g[59]

Case study

Creation of a new variety of sugarcane for multi-purpose use

Sugarcane can be produced for food, energy and fibre. Sugarcane be used for bioethanol, and a by-product of sugarcane can be used to generate electricity. JIRCAS (Japan International Research Center for Agricultural Sciences) has developed new multi-purpose sugarcane varieties with good yield of both sugar and fibre. It developed new breeding materials that produce high biomass yield in several unstable environments through intergeneric hybridisation between sugarcane and Erianthus. For this purpose, it established techniques for evaluating important characteristics related to biomass production of Erianthus in stress conditions and for selecting intergeneric hybrids using DNA markers.

"High-Yielding Biomass Crops" Development of technologies for the breeding and utilisation of promising high-yielding biomass crops in unstable environments | Japan International Research Center for Agricultural Sciences | JIRCAS

New design of cropping system for sustainable agriculture

To halt the ongoing decline in farmland biodiversity, despite decades of conservation efforts, there are increasing calls to design new farming systems based on ecosystem services or to transform existing farming systems based on taking environmental needs and values of the natural landscape into account. While most actions to improve biodiversity are currently being taken on the farm itself, there is a growing acceptance that it is necessary to take a broader approach which encompasses agricultural landscapes.

The proposed idea is to seek to restore semi-natural landscapes similar to primary natural landscapes, in which the biodiversity of ecosystems plays a major role. This will be important mainly in post-industrial regions which require specific attention with regard to regeneration of the environment, but not only there. The application of the new idea of Integrated Eco-land Farming requires that flower strips and undersowing with living mulches be taken into account and that agrotechnical treatments be limited in a defined production area, which extends beyond the boundaries of the individual farm (Figure 9.3). Only such an approach can help to bring about the comprehensive regeneration of natural areas, guaranteeing the sustainable and lasting development of the natural region as a whole.

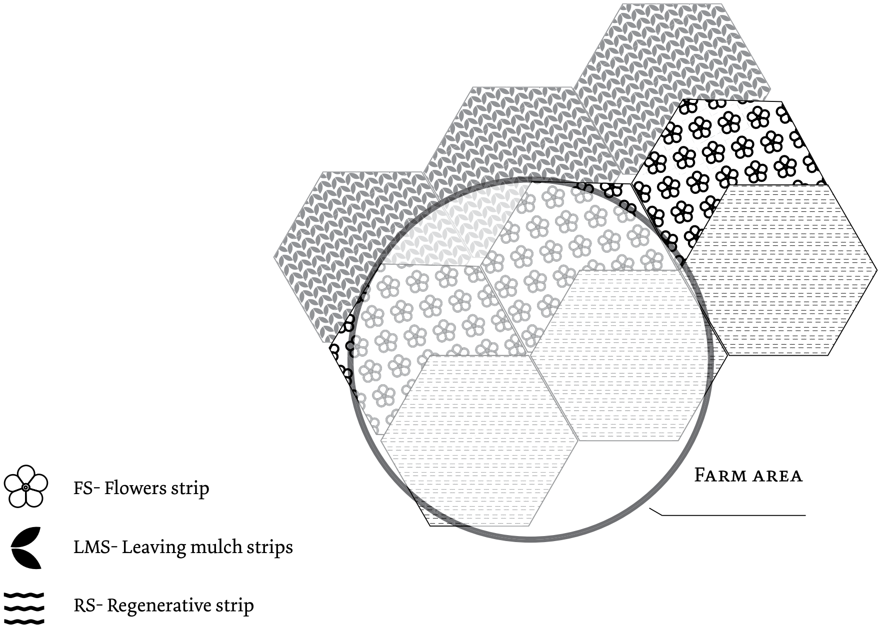


Figure 9.3 Diagram of the transformation of the agricultural landscape based on the idea of integrated eco-land farming.

Moreover, in our view (Figure 9.4), sustainable agriculture should encompass four components: the integrated farming system (IFS), integrated crop management (ICM), integrated pest management (IPM), and integrated eco-land farming (I–ELF). The taking into account of the above components strengthens the positive role of the sustainable production system in the shaping of the natural landscape, due to the greater importance of integration of its individual elements.

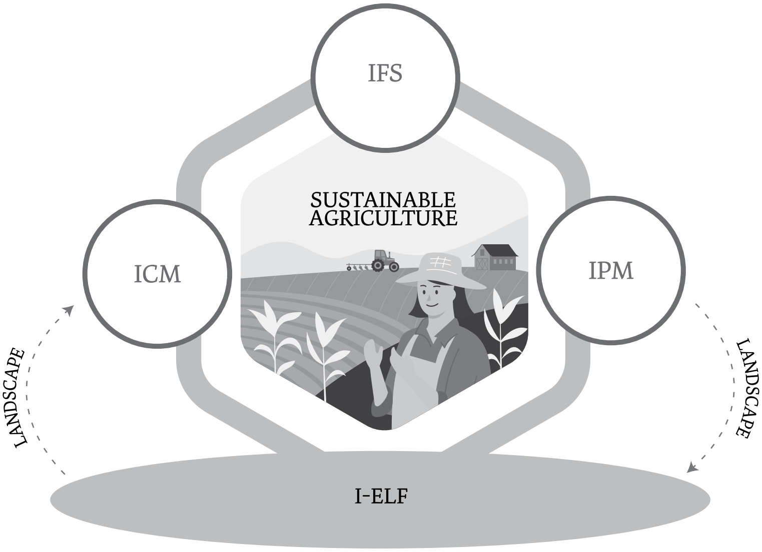


Figure 9.4 Transition in the main principles of integrated eco-land management. ICM – Integrated Crop Management; IFS – Integrated Farming System; IPM – Integrated Pest Management; I–ELF – Integrated Eco-Land Farming.

Integrated Farming System (IFS) is a sustainable agricultural approach that combines the cultivation of crops and the rearing of livestock in a mutually beneficial manner. This farming system offers several advantages, including increased ecosystem services, minimised environmental impact, and sustained farm profitability. By integrating crops with livestock, farmers can optimise resource utilisation, reduce the need for external inputs, and promote soil health. Additionally, this approach contributes to increasing biomass production, which is essential for the development of the bioeconomy. Integrated farming systems play a crucial role in supporting the transition towards a low-carbon economy and the achievement of sustainability goals. Components of the Integrated Farming System (IFS) include animals (pig farming, poultry farming, duck farming, fish farming), arable crops, vegetables, mushroom cultivation, fruit cultivation and vermicomposting. The Integrated Farming System (IFS) is based on the concept that 'there is no waste' and 'waste is only a misplaced resource', which means that waste from one component becomes an input for another part of the system. The IFS approach is considered to be the most powerful tool for enhancing profitability of farming systems, especially for small and marginal farmers to increase their yields.

Integrated Farm Management system as an holistic approach for farm self-sufficiency

The Integrated Farm Management (IFM) system consists of bringing the cultivation of plants and the breeding of farm animals together in a mutual partnership in order to have a beneficial impact on the environment and profitability of the farm. According to Kashyap et al.,[60] the components of IFM are the cultivation of field crops, gardening, the breeding of farm animals, as well as mushroom farming and fish farming. These components are used to create integrated systems including crop–livestock–forestry farming systems, crop–fish–poultry farming systems, and crop–livestock–poultry–fishery farming systems. Integration of the different systems guarantees growth and stability of production. It also guarantees the recycling of residues and optimisation of use of resources.

Integrated farming systems are being promoted in many regions of the world for economic and environmental reasons. Examples include cultivation of cereals and vegetables, animals (poultry) production and mushrooms. In order to cultivate mushrooms, straw residue is composted to produce manure. Poultry generates income from eggs, meat, manure and biofertiliser for vegetables.[61]

A more broad-reaching proposal is the idea of **Integrated Eco-land management** of farmland, which includes practices to:

- prevent land conversion and protect vulnerable lands;
- prevent and mitigate land degradation and restore degraded soils;
- improve soil-water storage;
- manage soil organic matter for soil carbon sequestration;
- manage and enhance soil fertility;
- promote integrated soil–crop–water management and integrated agroforestry and agrosilvopastoral systems;
- regeneration of agro-environments (e.g. managing grazing and livestock; rainwater collection; flower strip management; living mulching; precision agriculture).

Integrated Pest Management (IPM) aims to manage pest populations below the economic threshold so that pests do not destroy the crop. One method of pest management is the push–pull method, which involves controlling the behaviour of insect pests and their natural enemies. This approach uses stimuli which are not very attractive to pests (push) and stimuli which are attractive to other pests (pull).[62] Another approach is to employ agrotechnics. Phytosanitary plants (oats, mustard) are grown in crop rotation to control pests and insects.

Integrated Crop Management (ICM) is a system of crop production which conserves and enhances natural resources while producing food on an economically viable and sustainable foundation. It is based on a good understanding of the interactions between biology, environment and land management systems. Integrated crop management promotes innovative long-term solutions that support agricultural productivity and protecting and enhancing natural resources. ICM includes management of soil, cropping systems, crop fertilisation, seeds material, water and pests.

Integrated Eco-Land Farming (I-ELF) combines the most important principle of sustainable agriculture. I-ELF highlights the necessity to implement horizontally the sustainable practices to ecosystem through treating farm as a part of the whole agro environment. The concept of Integrated Eco-Land Farming (I-ELF) as an comprehensive sustainable land management assume ecological practices implemented horizontally from farm to farm in order to have an impact on the entire landscape and supporting the complexity of agroecosystem in relation to environment. Farmers communicate with each other, so that individual decisions about farm management (e.g. cropping system) have a positive impact on soil regeneration and biodiversity of farmlands. A holistic approach to boosting the eco-land management practices not only on a farm–farm level is needed to supply good-quality biomass. The I-ELF concept focus on harmony among plants and animals in the agro-ecosystem, and maintenance of spatial and temporal complexity in arable crops and landscape. Soil quality is treated as an integrator of ecological processes with land farming to enhance crop productivity. It is therefore necessary to assess soil and land resources to help land users select and adapt new eco-strategies for safeguarding essential ecosystem services and improve livelihoods and well-being. The I-ELF concept includes adaptation of new cropping systems (e.g. DRIP cropping system, multilayer cropping system) into practice in an integrated way in order to maintain productivity and restore degraded land.[63] Sustainable agriculture has major positive impacts on ecosystem diversity. By increasing crop diversity in agricultural systems, soil–plant–land diversity can be effectively promoted. Klimek-Kopyra et al.[64] propose a holistic approach involving the creation of an innovative cropping system, called the ‘DRIP cropping system’, aimed at ‘saturating the soil with good practices’, i.e. **d**iversification, **r**otation, **i**ntercropping, and **p**rairie strips, in order to create a ‘healthy soil zone’ which will be highly productive for plants.

Current farming practices are increasingly considered to be unsustainable, posing a serious threat to the environment. To achieve European sustainable agriculture goals, the role of integrated crop production and of systems aiding its development will have to be strengthened. Conventional farming ensures high production of biomass, but at significant cost to the environment, while transitioning to organic farming does not guarantee the high yield needed to feed a growing global population. To compare the environmental efficiency of different farming systems, new ideas and the spectrum of their impact on the natural landscape, it is necessary to adopt a holistic methodical approach, which is guaranteed by Life Cycle Assessment (LCA).

9.5 Life Cycle Assessment (LCA) and its application in measuring the environmental sustainability of production systems and practices

As an environmental accounting mechanism, Life Cycle Assessment method has developed dramatically to provide a very effective and credible tool to contextually calculate the risks and threats of environmentally destructive behaviour, namely: (1) human population growth; (2) over-consumption of natural resources; and (3) pollution of air, water, and land through the production and release of gases and waste material into the atmosphere and physical environment. An important example is the production of methane gas. The climate change potential of methane released into the atmosphere is 25 times higher than for carbon dioxide,[65] thus methane emissions released from poorly managed agricultural production systems or biogas plants can significantly affect the configuration's GHG performance. Some two-thirds of the emissions from global food systems come from the land-based sector, comprising agriculture, land use and land use changes. In terms of their share of all anthropogenic GHG emissions, food systems of industrialised countries are broadly stable, at around 24%, while, in developing countries, it has decreased notably – partly due to very high increases in non-food emissions – to 39% in 2015 from 68% in 1990.[66] By nature, the goal of an LCA is not just to understand all the life cycle stages associated with a product, but also all the differences or trade-offs among different environmental impacts. To achieve more sustainable production and consumption patterns, we must consider the environmental implications of the whole supply chain of products, both goods and services, their use, and waste management, i.e. their entire life cycle from "cradle to grave".[67,68] By characterising, quantifying and interpreting energy and other environmental flows from "cradle to grave," LCAs can play an important role in assessing the GHG emissions associated with agricultural products, which tend to be more dependent on regionally specific conditions and factors than industrial products. These represents important opportunities along the production and value chain for mitigating energy consumption and reducing GHG emissions. The "cradle to gate" analysis phase deals with the production stages that bring foodstuffs to the farm gate – including inputs such as fertilisers. This phase is now the leading contributor to overall food-system greenhouse gas (GHG) emissions. In 2015, food-system emissions amounted to 18 Gt CO_2 equivalent per year globally, representing 34% of total GHG emissions. The largest contribution came from agriculture and land use/land-use change activities (71%), while the remainder were from supply chain activities: retail, transport, consumption, fuel production, waste management, industrial processes and packaging.[69] Methane (CH_4) accounts for around 35% of food-system GHG emissions, broadly the same in developed and developing countries, and mostly stems from livestock raising and rice cultivation.[70]

9.6 Making LCAs more functionally effective for agricultural systems

For LCA studies in agriculture to be credible and correct they need to cover all central environmental impacts. These impact categories for classical LCAs either need to be adapted or not applied.[71] In particular, the term 'land use' must be properly defined. Depending on the objectives of LCA assessments, different functional units can be used. However, the functional unit product (e.g. milk, meat, etc.) in agricultural LCAs should be used carefully since the motivation for using this technique does not often apply. In the categories of biodiversity (excluding the number of species per area), landscape image and animal husbandry, the whole farm is the only meaningful unit. Only common comparative abiotic categories can also be related to the livestock unit (stocking rate), or to the product unit of milk (kg).[72,73]

Pelletier[74] describes two important LCA applications for optimising the whole farm unit application in LCA investigations. Figure 9.5 offers a conceptual framework for decision making during the development of LCA investigations for agricultural systems.

- **Industry Average Life Cycle Assessment**

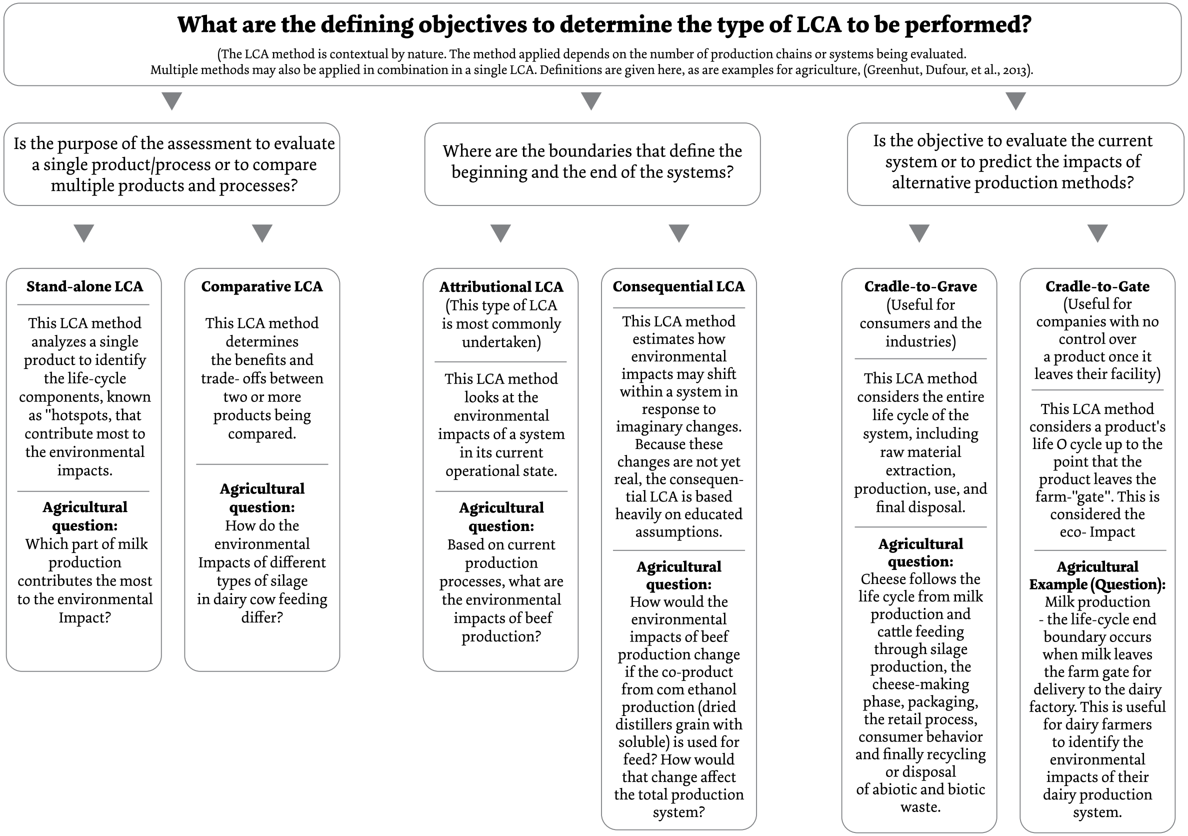
The purpose of this kind of LCA is to develop a baseline understanding of the magnitude and extent of resource demands and environmental impacts associated with the production of a particular commodity (e.g. milk) at a regional or national scale. This type of study is well suited to use for the purpose of comparing impacts between different kinds of commodities available in the marketplace to support prioritising interventions or environmentally informed consumption choices. It is part of the LCA method to also provide mitigating actions.

- **Producer-level Life Cycle Assessment**

This more contextualised approach to LCA investigations is well suited to better serve the needs of individual producers. Farming system typology is normally the basis of implementation. This approach may be very effective in identifying beneficial practices in the light of specific climatic, geographical, or socio-economic constraints, and with respect to known, regionalised environmental sensitivities. The rigorous, context appropriate models of analysis and data assembled during the study, makes this approach beneficial for certification schemes (Figure 9.5).[75]

9.6.1 Considering some practical applications to agricultural systems and their general findings

Whole-system LCA analysis for agricultural production systems may be beneficial when trying to estimate which unit processes significantly contribute to



What are the defining objectives to determine the type of LCA to be performed?

(The LCA method is contextual by nature. The method applied depends on the number of production chains or systems being evaluated. Multiple methods may also be applied in combination in a single LCA. Definitions are given here, as are examples for agriculture, (Greenhut, Dufour, et al., 2013).

Is the purpose of the assessment to evaluate a single product/process or to compare multiple products and processes?

Stand-alone LCA

This LCA method analyzes a single product to identify the life-cycle components, known as "hotspots, that contribute most to the environmental impacts.

Agricultural question: Which part of milk production contributes the most to the environmental Impact?

Comparative LCA

This LCA method determines the benefits and trade- offs between two or more products being compared.

Agricultural question: How do the environmental Impacts of different types of silage in dairy cow feeding differ?

Where are the boundaries that define the beginning and the end of the systems?

Attributional LCA (This type of LCA is most commonly undertaken)

This LCA method looks at the environmental impacts of a system in its current operational state.

Agricultural question: Based on current production processes, what are the environmental impacts of beef production?

Consequential LCA

This LCA method estimates how environmental impacts may shift within a system in response to imaginary changes. Because these changes are not yet real, the consequential LCA is based heavily on educated assumptions.

Agricultural question: How would the environmental impacts of beef production change if the co-product from com ethanol production (dried distillers grain with soluble) is used for feed? How would that change affect the total production system?

Is the objective to evaluate the current system or to predict the impacts of alternative production methods?

Cradle-to-Grave (Useful for consumers and the industries)

This LCA method considers the entire life cycle of the system, including raw material extraction, production, use, and final disposal.

Agricultural question: Cheese follows the life cycle from milk production and cattle feeding through silage production, the cheese-making phase, packaging, the retail process, consumer behavior and finally recycling or disposal of abiotic and biotic waste.

Cradle-to-Gate (Useful for companies with no control over a product once it leaves their facility)

This LCA method considers a product's life O cycle up to the point that the product leaves the farm-"gate". This is considered the eco- Impact

Agricultural Example (Question): Milk production - the life-cycle end boundary occurs when milk leaves the farm gate for delivery to the dairy factory. This is useful for dairy farmers to identify the environmental impacts of their dairy production system.

Figure 9.5 A summary of the decision-making process followed during the development of LCA investigations for agricultural systems (based on Greenhut et al.).

the environmental impacts of the production system. Comparisons between model results, are, however, often difficult due to the assumptions required for estimating emission factors. The IPCC[76] guidelines are often used to estimate field-level, enteric and manure emissions, provided, however, several key assumptions are made to meet the characteristics and requirements of the production system. A standardised protocol to estimate emissions in agroecosystems is needed so production systems and management practices can be compared with a higher degree of confidence.[77] Currently, such protocols are not generally available for whole-farm LCA analyses. Regardless of these problems, LCA studies are effective in identifying areas of a production system that place the greatest burden on the environment. An important example is the major group of studies suggesting enteric emissions from ruminants were responsible for a majority of the GHG emissions. Grainger and Beauchemin,[78] following studies into dietary manipulation to reduce enteric emissions, suggest that this technique may provide a feasible mitigation alternative. Also, increasing the fat and crude protein content in the diet increases digestibility and reduces enteric emissions. It is, however, also true that increasing the crude protein content increases the amount of nitrogen excreted (increasing the eutrophication potential).[79] An important aspect to remember is that LCA methodology offers important information for use in mitigating the potential negative environmental (climate change), economic (optimising resource utilisation) and societal (health and welfare) impacts.

Based on the explanations and options offered, a brief review of case studies and examples are offered to demonstrate the range-of-use and effectiveness of LCA investigations in analysing the environmental sustainability of some of the most prominent agricultural systems in Europe, namely:

- ***Beef-rearing systems***

Lupo et al.[80] illustrated the use of LCA methodology in evaluating the environmental impacts of four different beef-producing systems – based on concerns from policy makers, producers and consumers. Over the last 20 years, a shift in the industry has been seen, with more cattle being raised on fewer farms. There has also been a gradual decline in the number of heads. Beef production, however, has continued to increase. This increase in production can be largely explained by an increase in average dressed weight (carcass weight) due to a specialisation in beef production phases and a high grain-based finishing diet. Due to different finishing weights, the functional unit (FU) for the study was 1 kg of standard carcass weight. The LCA model followed a “cradle-to-gate” approach and incorporated all major unit processes, including mineral supplement production.

Enteric emissions and manure emissions and handling were consistently the largest contributors to the LCA-assessed environmental impacts. There was little variability between production scenarios except for the grassfed scenario, where the greenhouse gas (GHG) emissions were 37% higher due to a longer finishing time and lower finishing weight. However, reductions in GHG emissions (15–24%) were achieved when soil organic carbon accrual was considered, and this may be a more realistic indicator. Manure emissions and handling were primary contributors to potential eutrophication and acidification impacts. This study provides an example of how LCA Model results can be used for guidance by producers, environmental practitioners and policymakers.

Cederberg and Stadig[81] analysed multifunction in beef production systems to determine to what extent the environmental burdens of these processes should be allocated to the product investigated. An important consideration is that milk and beef production systems are interlinked like communicating vessels. This means that changes in milk production systems will cause alterations in beef production systems. Therefore, the choice of allocation method between milk and meat has a decisive impact on LCAs of milk production and it is obvious that a monofunctional allocation approach gives limited information on how to develop and change milk and beef production in an environmentally friendly way. Since meat production in combination with milk can be carried out with fewer animals than in a sole beef production system, LCA analyses suggest that a reduction in biogenic emissions and less land to produce on, can be expected. It is, however, important to remember that indirect actions, increased milk yield per dairy cow or an increased replacement rate will change the environmental burdens outside the life cycle of milk because beef production systems will be affected. This is particularly important in European beef and milk production systems. Casey and Holden[82] applied a Life Cycle Assessment (LCA)-type method to quantify GHG emissions from typical Irish suckler-beef production systems. Results clearly suggest that integrated dairy–beef systems where dairy cows produce calves for beef production can significantly reduce GHG impacts because emissions were allocated between meat and milk production.

- ***Beef feedlot production systems***

Conflicting and mostly inconsistent reporting regarding strategies that blend efficiency and C-sequestration, or trade off one for the other, as to whether finishing cattle in feedlots versus field grazing is more likely to reduce net beef GHG emissions, have been points of contention in the literature. Many studies show that feedlots are the more GHG-efficient beef-finishing strategy because of reductions in enteric CH_4 emissions resulting from more digestible feed and greater stocking densities, compared to more fibrous diets and longer finishing times in grazed beef.[83,84,85,86] Other studies argue that finishing cattle on pasture or rangeland, rather than in feedlots, is more beneficial to the climate because it promotes land-based C-sequestration and requires less climate-intensive feed crops while also supporting natural grassland conservation and animal welfare.[87,88,89]

- ***Grazing systems***

Grazing-based strategies for climate mitigation have been shown to have varying effects on C-sequestration rates among sites and over time (Henderson et al., 2015). In particular, the extent of soil degradation varied among regions leading to different baselines for comparison with increased soil C-storage. Promotion of soil C-sequestration is typically more successful on degraded lands that have lost large portions of their native soil C and it has been estimated that restoring depleted C-stocks represents 47% of the potential for climate change mitigation on agricultural and grasslands.[90,91] With respect to grazing systems, the implementation of best management practices can offset enteric emissions through SOC accrual. Furthermore, management-intensive grazing improved plant quality and, hence, feed conversion efficiency, resulting in a 22% reduction in enteric emissions.[92]

9.6.2 Discussion on the limitations and challenges of the LCA methodology in its application in the bioeconomy

As seen in the previous discussions, literature reviews and studies suggest that it is important to integrate biodiversity into LCA investigations, as an important step towards fully understanding the environmental impacts of food systems. Although there is increasing recognition of the ways agro-ecosystems stand to both benefit from and influence biodiversity, characterising biodiversity impacts remains challenging due to scale dependence and differences among taxa. Although holistic evaluations remain the ultimate objective of LCA models, it remains increasingly challenging to include every relevant input within the system boundary. Findings from the literature also suggest that increases in the complexity of production systems also complicate the structure and interpretation of the analyses. It is abundantly clear that results can differ immensely depending on where the LCA model defines the beginning and end of the product's life cycle. Furthermore, some factors are complex and difficult to quantify. For example, it is challenging to define parameters for measuring impacts on land use, biodiversity, human health and a variety of other factors. Constant reminders are issued that remind researchers that the validity of an LCA analysis depends on the integrity of its underlying data and on adequate calibration. In biological systems such as agriculture that are inherently dynamic and variable, it can be even more challenging to obtain data that characterise the many possibilities and interactions in the system. In nearly all literature, the critical importance of the transparent communication of its underlying assumptions, boundaries and data sets to establish and maintain the credibility and application of any LCA model, is emphasised.

The potential important potential of LCA frameworks for bioeconomy decision-making must, however, not be underestimated or neglected. It is well accepted that the impact of agricultural production on the environment is a major issue since it contributes to placing an additional burden on already strained ecological health and natural resources.[93] The Organisation for Economic Co-operation and Development (OECD) recognised this fact as early as 1997 and published important guidelines on the development of environmental indicators for agriculture.[94] But researchers point out that the huge variety of environmental indicator sets makes the comparisons between them (and subsequently the results of LCA analyses) very difficult.[95] Frameworks for LCA have also developed the interpretive ability to apply an environmental indicator to either represent an anthropogenic pressure affecting the environment, the state of the environment itself, or a societal response to modify the pressures on the state of the environment. Of course, the conflict potential and need for policy decision-making on this matter is evident. LCA can provide information about the local effects of livestock production[96] or alternative modes of production, but this requires a greater degree of site-specific knowledge and data.

9.7 Primary production (natural cycles) in the context of innovation

Sustainable innovations in plant production play a crucial role in mitigating the challenges posed by climate change, ensuring food security and averting the threat to soil fertility.[97] This chapter explores several key areas in which sustainable practices have been implemented, including carbon footprint reduction, soil fertility improvement, nutrient recycling, the introduction of regenerative and precision farming, and the development of a concept of bioeconomy.

Implementing sustainable practices has resulted in a significant reduction in the carbon footprint of plant production. For instance, the use of ***precision agriculture techniques***, such as GPS-guided machinery and drone technology, allows farmers to optimise the application of fertilisers and pesticides, reducing their overall usage. Furthermore, the adoption of renewable energy sources, such as solar panels and biogas plants, in agricultural operations has further minimised carbon emissions. Regenerative agriculture plays a pivotal role in the reduction of carbon emissions by implementing practices such as minimising soil disturbance and incorporating permanent vegetation cover.[98] These practices enhance the process of carbon sequestration, ultimately leading to reduced reliance on fossil fuels and bolstering soil fertility.[99]

Biofuel production from different sources of biomass is another example of innovation, which is being implemented in the agricultural sector. Currently, there is a tendency to increase the production areas for cultivation of herbaceous plants of the *Poaceae* family such as Miscanthus.[100] This phenomenon can be explained by high growth rates and the prospects for its application in the bioeconomy. Miscanthus is a very valuable raw material as it accumulates a large amount of solar energy. The main advantage of this plant is its high yield. Miscanthus is a promising raw material for biofuel and bioethanol production, because this species can be used to produce biologically active substances. Vanillin, vanillic acid, syringaldehyde, para-hydroxybenzaldehyde, para-coumaric acid, campesterol, stigmasterol, β-sitosterol, stigmasta-3,5-dien-7-one, stigmast-4-en-3-one, stigmast-6-en-3,5-diol, 7-hydroxy-β-sitosterol, and 7-oxo-β-siterol determine the main phenolic compounds and sterols of both *Miscanthus* × *giganteus* core and bark (*Miscanthus* × *giganteus* J.M. Greef, Deuter ex Hodk., Renvoize).[101]

Throughout its development since Neolithic times, human civilisation has achieved many goals, which have led to changes to many ecosystems. Progress measured in terms of productivity, in terms of both animal and plant production, has had a significant impact on the amount of biomass produced at the expense of the limitation of biodiversity. To meet the challenges of current and future civilisation, farm management according to the idea of I-ELF, based on the principle of sustainable development, appears to be the only right road to development. It is thought that the 'post-industrial' era, which is currently taking place, will give way to changes not only in the management of (primary and secondary) biomass, but also in the systemic approach to the protection of natural resources. The main element of the post-industrial revolution is the bioeconomy as a catalyst of systemic changes encompassing all sectors of basic production, which use and produce biological resources, as well as economic and industrial sectors that rely on these resources and processes to generate food, animal feed, energy, and services.

Notes

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10 Biotechnological processes in the bioeconomy

Anna Gorczyca, Maria J. Chmiel and Maciej Guzik

10.1 History and evolution of biotechnology

Biotechnology has been part of human life since ancient times, but it started to develop rapidly at the turn of the 20th and 21st centuries. The huge contemporary interest in biotechnology is a result of the unlimited potential of the benefits it brings in all areas, above all those related to such basic human needs as food, health and quality of life. Biotechnology also provides solutions to today's most pressing environmental problems, including alternatives to nearly depleted energy resources from fossil fuels, or the adaptation of primary production to ongoing climate change. Thanks to biological resources subjected to a variety of technologies, in other words biotechnology, our lives are much more comfortable and safe, and limits have been placed on our activities that are damaging to the environment. This illustrates that biotechnology is the actual foundation of the bioeconomy. But this did not just happen from one day to the next – people have been using living organisms for their own needs since ancient times, and, with the growth in knowledge, this has become increasingly common gradually leading to the current state of affairs today.

It is hard to point with absolute certainty to the "parents" of biotechnology, but there is no doubt that the first person to use the term was the Hungarian scientist and agricultural engineer dealing with animal husbandry and meat processing, Karl Ereky, who employed it in 1919, when he published a book entitled: *Biotechnology of meat, fat and milk production in an agricultural large-scale farm.*[1] Innovative at the time, Karl Ereky's vision is now being realised by thousands of companies and research institutions worldwide. Since the term biotechnology was first coined, its definition has been constantly evolving. In practical terms, the main purpose of biotechnology is to transfer its numerous benefits to human life. However, it should be remembered that, in addition to its beneficial applications, biotechnology may also give rise to products that can be dangerous or even fatal, such as those used in bioterrorism.

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Over the course of history, our needs have evolved, and so has biotechnology. Its development has fundamentally been based on observations and the application of these observations in various practical scenarios. Studying the development of biotechnology, it is possible to distinguish three main stages of development:

- ancient biotechnology,
- classical biotechnology,
- modern biotechnology.

It is remarkable that some ancient technologies are still being used today, but their effectiveness, efficiency and profitability continues to be systematically improved. The creation and evolution of some of the most important discoveries in the field of biotechnology are shown in Figure 10.1.

Solutions of **ancient biotechnology** were related primarily to basic human needs. This stage, above all, corresponds to the domestication of plants and animals as a result of problems with guaranteeing food from natural resources. This marked the beginning of the first human activity on our planet, one which remains fundamental to this day, namely agriculture. Once people had adopted appropriate species to cultivation and breeding in their own settlements, the problem of preservation and storage of food arose. People started, without knowing causes of phenomena, use of microorganisms for the processing of food. Cheeses started to be produced by adding rennet (an enzyme occurring

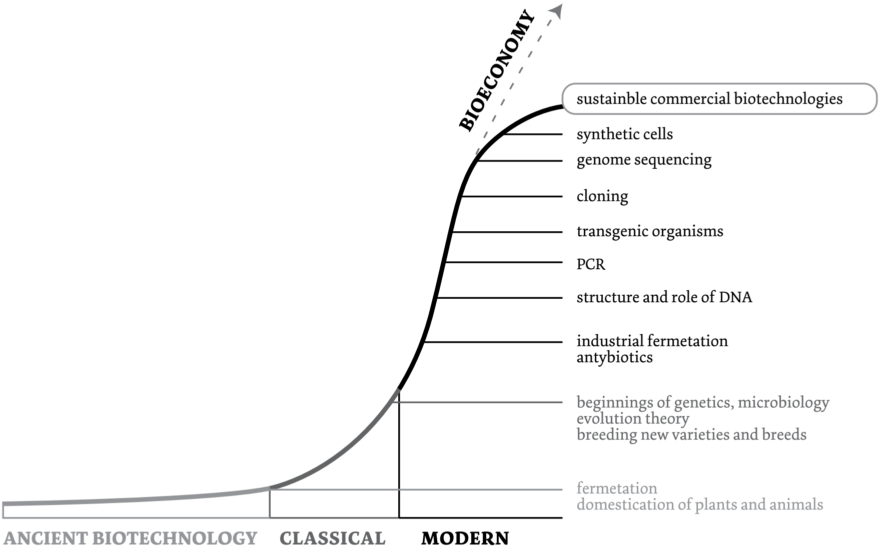


Figure 10.1 Categorisation and evolution of biotechnology.

Source: Own elaboration.

in the stomach of calves) to sour milk, which in turn is only possible when milk is exposed to microbes. The next breakthrough in food processing was in the use of yeast. To this day, they continue to be used in the production of basic products such as bread and fermented beverages. Another example of ancient biotechnology can be considered to be the first successful attempts to cross-breed animal species.[2]

The second phase in the evolution of biotechnology, referred to as the **classical stage**, only commenced around 1800. The 19th century can be considered to be a decisive period in the development of science, allowing us to understand the processes used in ancient biotechnology. This stage is inextricably linked to the genetics of organisms. The Czech scientist and monk, Gregor Johann Mendel (1822–1884), now recognised to be the father of genetics, was the first to present the laws of inheritance, when carrying out studies on *Pisum sativum*. He provided experimental proof that invisible internal units of information account for observable traits, and that these "factors" – later called genes – are passed from one generation to the next.[3] Mendel's work did not receive recognition among his contemporaries, however; it took another 34 years for it to be rediscovered by Hugo de Vries, Erich Von Tschermak and Carl Correns, who validated Mendel's theory. Another parallel breakthrough was the theory of evolution proposed by Charles Darwin (1809–1882), who claimed that all living species share the same origin. This opened the way for research into model organisms, the conclusions of which came to be more universally.[4] Biotechnology as we know it today would not exist also without the groundbreaking discoveries of Louis Pasteur (1822–1895), a pioneer in the field of microbiological research, who discovered the necessity of pasteurisation. Further discoveries, such as made by Robert Brown (nucleus in cells) and Fredrich Miescher (who identified the nuclein), became the basis of modern molecular biology. This related to the DNA as a genetic material and the role of DNA in the transfer of genetic information. In 1881, Robert Koch (1843–1910) described the first ever solid medium (potato slices) for the cultivation of bacteria. Walter Hesse (1846–1911), along with his wife Fanny, discovered agar and it was possible to commence intensive laboratory studies with microorganisms. These and other studies resulted in a description of chromosomes as an organised structure of DNA, protein present in cells, as well as a regulatory elements and nucleotide sequences in DNA and other phenomena in the field of genetics. At this time, the development of biological sciences reached an exponential phase. The principles of the genetics of inheritance were formulated, along with the theory of the gene, genotype and phenotype. At around the same time, Alexander Fleming (1881–1955) discovered antibiotics and observed that one microorganism can be used to kill another, thereby revolutionising the fight against infectious diseases.[5,6] At the same time as the development of genetics, numerous discoveries were being made in industrial biotechnology. Chaim Weizmann (1874–1952), considered to be the founding father of industrial fermentation, used a pure microbiological culture in an industrial process for the first time. He developed a process in which acetone, n-butanol and ethanol were produced as a result of bacterial fermentation. This development was related to the need to produce acetone used in explosive materials during World War I.[7]

The main, most dynamic development in biotechnology should, however, be considered to have taken place only in the mid-20th century, after the end of World War II. **Modern biotechnology** began with explanation of the secrets of DNA, as a genetic material, the presentation of the structural model of DNA – in other words, the double-helix model, the explanation of phenomena related to DNA replication of and their role in inheritance, the concept of the operon, the concept of cytoplasmic hybridisation and the production of monoclonal antibodies, which ultimately revolutionised diagnostics and opened the way for important scientific discoveries.[8,9] Modern biotechnology proper was born in the 1970s, when Paul Berg successfully spliced DNA molecules, and Herbert W. Boyer and Stanley N. Cohen then perfected this technology, transferring genetic material to bacterial cells so that it could be cloned. Intensive commercialisation of the newly established biotechnology industry followed in the 1980s, when the US Supreme Court gave its decision in the *Diamond v. Chakrabarty* case concerning the patenting of a genetically modified microorganism, a *Pseudomonas* bacterium capable of breaking down crude oil. Since then, it has been possible to patent a living organism. This was a breakthrough which allowed numerous biotechnological discoveries to be patented and led to research being transferred from scientific institutions to commercial companies, clearly accelerating the implementation of scientific discoveries in practice.[10] The turn of the millennium was a period of very intensive integration in the fundamental sciences, something which was of special significance for scientific progress and the commercialisation of research. In laboratories, work commenced on the synthesis, amplification and transformation of DNA. An adult animal was cloned (Dolly the sheep) and the human genome was sequenced. Advances in molecular techniques led to the need to analyse huge amounts of data, resulting in the creation and development of bioinformatics, and IT tools allowed results obtained by scientists to be collected and processed on a global scale. IT tools and networks can be considered to have enabled progress in biotechnology on a scale that would not have been possible before the era of computerisation.[11]

The now widely accepted definition of biotechnology is *The integration of natural sciences and engineering sciences in order to achieve the application of organisms, cells, parts thereof and molecular analogues for products and services* and refers to the interdisciplinary importance of this area of science.[12] In the 21st century, biotechnology has become such a broad area of science and industry, and of our daily lives, that the concept was developed of dividing it up into colours which are associated with the areas of its use.[13] This concept is called the "biotechnology rainbow". Table 10.1 presents the identified branches of biotechnology and their description.

Taking account of the current state and diversity of the branches of biotechnology, it should now be considered to be one of the main strategic pillars

Table 10.1 Branches of biotechnology and areas which they concern divided up according to the rainbow code of biotechnology

Biotechnology colour	*Area of science and practices,* covers*, examples*
Red	**Medicine, pharmacy and health care** *diagnostics techniques and therapeutics* vaccines, antibiotics, biopharmaceuticals, pharmaceutical enzymes and metabolites, regenerative therapies, biocompatible implants
White	**Industry** *biological systems in industrial production and environmental protection* biocatalysis and bioprocesses, useful chemicals, enzymes as industrial catalysts, fuels/energy from renewable biomass
Green	**Agriculture** *improving production, implementation of methods of production which are more environmentally friendly* breeding technology, selection, design of transgenic crops, bioproducts (fertilisers, plant protection agents, stimulants)
Blue	**Water** *marine food, marine biodiversity as sources of new pharmaceuticals or industrial enzymes* aquaculture, food rich in omega-3 fatty acids, micro- and macroalgae; food additives, nutraceuticals, industrial enzymes
Gold	**Bioinformatics** *computational techniques allowing biological data* genomics, proteomics, metabolomics, interactome large-scale biological data processing; bionetwork, molecular interactions, protein functionally mapped
Grey	**Maintaining biodiversity and restoring ecosystems** *bioremediation, keeping a register of species present in ecosystems* phyto-, phyco- and bacterioremediation, gene banks, genetic analyses for the classification and cloning of endangered species
Yellow	**Food production** *fermentation, preservation, functionalisation and new food sources* wine, cheese, beer production, sourcing, insects, algae as food, artificial food
Brown	**Arid, saline soils** *management of resources under arid or saline conditions* improved seeds, GMO varieties for dry areas, post-harvest soils conservation, saline agriculture
Violet	**Legal, ethical and philosophical aspects of biotechnology** *patenting; legalisation and legal regulation; protection of intellectual property rights; use of animals in scientific research*
Dark	**Bioterrorism, biological weapons, warfare** *use of toxins of biological origin or microorganisms as weapons, use of microorganisms and toxins to cause disease and death*

of the global bioeconomy. In Europe, as early as 2020, the European Commission had noted that "*The next era of industry will be one where the physical, digital and biological worlds are coming together*." Such a combination is possible above all thanks to primary production, which includes green biotechnology and white industrial biotechnology. All the other branches of biotechnology complement this combination in the area of knowledge and/or practice. Development of the bioeconomy, which, according to its definition, "*promotes the production of renewable biological resources and their conversion into vital products and bioenergy for achieving [...] societal challenges [...] in the domains of food security, employment and competitiveness, climate change, sustainable management of natural resources and dependence on non-renewable natural resources*"[14,15] would be impossible without the progress which biotechnology has provided our society with, and especially its basic areas of activity in the green and white bands of the biotechnology rainbow.

10.2 Agriculture and green biotechnology

Modern biotechnology has a lot to offer agriculture, and green biotechnology is the best way of making agriculture sustainable and ensuring global food security and safety. When trying to define agricultural biotechnology, we can use the definition proposed by US Department of Agriculture: *Agricultural biotechnology is a range of tools, including traditional breeding techniques, that alter living organisms, or parts of organisms, to make or modify products; improve plants or animals; or develop microorganisms for specific agricultural uses.*[16]

10.2.1 Plant biotechnology

People have caused changes in the world of plants since the advent of agriculture, thus allowing development of human population. Civilisations could not exist without agriculture, and agriculture could not sustain the civilised world without continuously improved crop varieties. From this point of view, it becomes clear that plant breeding, which can now be described as plant biotechnology, is one of the main foundations of civilisation and is also of fundamental importance for the modern bioeconomy.

At the current stage of development of civilisation, it can no longer be denied that transgenic breeding is an inevitability of plant biotechnology, but conventional techniques are still very important. The oldest of these methods continues to be plant breeding based on observed variation by the selection of plants based on natural variants appearing in nature or within traditional varieties. Another technique is crossbreeding (hybridisation), which allowed significant progress to be made in obtaining desired traits. The crossbreeding of plants with appropriate traits and selecting offspring with the desired combination of traits as a result of specific gene combinations inherited from parent individuals is the basic technique that has been used since Mendel's discoveries were accepted. It is, however, a technique which takes significantly longer to achieve the desired outcome compared to molecular techniques and which is limited due to possibility of the genome variation, over which the creators of new varieties do not in principle have any influence because of genetic correlations between different traits, which may be due to genes with pleiotropic effects, to physical linkage between genes in the chromosomes, or to population genetic structure.[17] Currently, the conclusion reached by the scientific community is that, in order to meet the needs of the human population, it is necessary to use the most modern molecular methods which allow monitoring of the dynamics of genome recombination and the breeding of varieties gene by gene.

Genetically modified (GM) plants, which are also called transgenic or genetically engineered plants, are defined as plants having been produced using transgenic methods. According to the European Union (EU), genetically modified organisms (GMOs) are defined as *any organism, except humans, carrying an altered genetic material that does not occur naturally through natural selection or mating*. Plant biotechnology is based on changes aimed at: improving agricultural properties, increasing the yield of plants and quality of food obtained from them (improvement in nutritional value), improving post-harvest durability and mitigating environmental pollution. This is achieved, for example, by increasing their resistance to abiotic stress like drought, salinity or high/low temperatures; increasing tolerance to herbicides, insects and viruses resistance, improving growth rate, changes in the composition of the crop such as increased content of protein, fats/oils, and carotenoids or reduction of sugar content – which is important for food production sector, or plant-based remediation processes (e.g. removing heavy metals from the soil) – which are important for environment protection.[18]

The first GM plants were planted in fields in 1994. This was a variety of GM more rot-resistant tomato called FlavrSavr (Calgen Inc.). Although the commercialisation of this transgenic variety was unsuccessful just two years later (1996), the area under GM plants had already reached 1.66 million ha[19] (Brookes and Barfoot, 2013) and, in 2022, GM crops were being grown over an area of 202.2 million hectares. In the early 21st century, the global market for GM crops was dominated by such plants as: soybean, maize and cotton. The first GM soybean was used in the USA in 1996 by Monsanto. As early as 2022, the herbicide-resistant soybean GM accounted for 73.7% of its crops area. The first GM maize resistant to herbicide was commercialised in 1996, also by Monsanto. In the same year, GM maize with gen of crystal toxins (Cry) from the entomopathogenic *Bacillus thuringiensis* (Bt) bacteria was also introduced to the market. Bt GM maize has revolutionised pest control in many countries and opened the door to other Bt GM species. By 2022, maize was the second-most common GM crop (after soybean, excluding plants which are not grown for human consumption, such as cotton), with 66.2 mln hectares all over the world. GM plants cultivation has been growing dynamically, especially in the USA, Brazil and Argentina.[20] The size and scope of GM crops in the 11 leading countries worldwide in 2022 are shown in Figure 10.2.

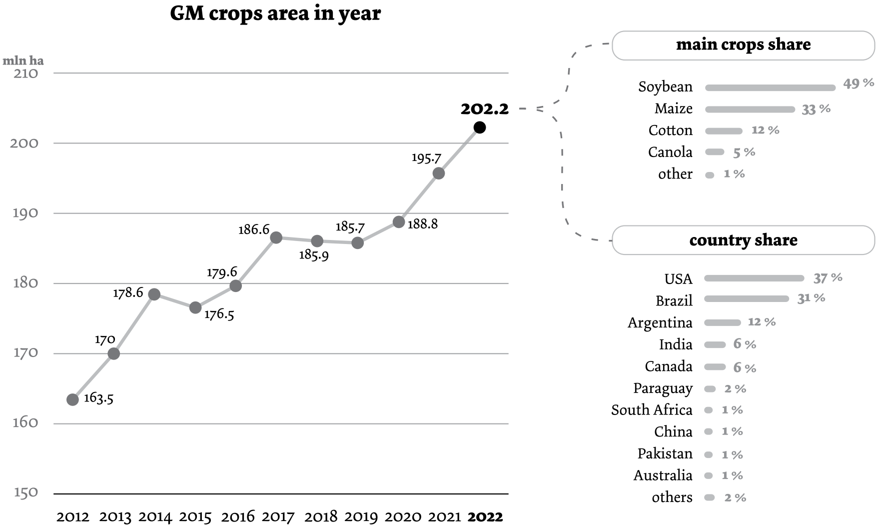


Figure 10.2 Development in GM crops since 2012 and 2022.

Source: Own elaboration, based on: https://gm.agbioinvestor.com.

Currently, the list of GM includes plants such as: soybean (mainly herbicide-tolerant, insect-resistant or with altered oil profile), maize (mainly insect-resistant and/or herbicide-tolerant), cotton (insect-resistant or herbicide-tolerant), herbicide-tolerant oilseed rape (canola) and alfalfa, rice (pest-resistant, enriched with beta-carotene) and also non-browning apples, eggplant (insect-resistant), papaya (ringspot virus-resistant), pineapple (increased levels of carotenoids and inhibited flowering), potato (reduced black spot bruising, levels of free asparagine and sugars or virus-resistant), squash (virus-resistant) and herbicide-tolerant sugarbeet,[21] tobacco and some others. The only GM crop grown in the EU Single Market is maize (in Spain and Portugal, and in small areas of Slovakia and the Czech Republic). It should be underlined that the most recent scientific research indicates that GM crops have a significant impact on the global bioeconomy. The positive impact on yields is particularly noticeable in developing countries. Data analyses conducted have confirmed that, without GM crops, the world would need an additional 3.4% of arable land to maintain global agricultural production, which is particularly important in the context of land scarcity and the bioeconomy's need to grow plants providing biomass for energy or industrial purposes. Scientists emphasise that bans on GM crops are limiting the global benefits of the adoption of GM to one-third of its potential, and that developing countries would benefit most from the lifting of those bans.[22] Besides the direct production of GM crops for food and industrial purposes, another important sector of modern plant biotechnology has become exploiting their potential as biological factories, that is as bioreactors for the molecular farming of recombinant macromolecules, such as blood proteins, vaccines and antibodies and raw materials for cosmetics. The first reports of the production of mammalian proteins in plants appeared at the end of the 1980s and, since then, the concept of "molecular farming" has been slowly gaining ground in the global bioeconomy. The concept of molecular farming or "biofarming" was introduced by Fischer et al.,[23] describing "the production of recombinant proteins in plants".

Other plant biotechnologies which are important to the modern bioeconomy also include soilless growing systems, such as *in vitro* farming, hydroponics, aquaponics, aeroponics and vertical farming. Since its discovery by Gottlieb Haberlandt (1854–1945) at the start of the 20th century, *in vitro* plant culture has, above all, been used for micropropagation, in other words, vegetative propagation with the aid of tissue cultures. Micropropagation has several advantages compared to traditional vegetative propagation methods, including the preservation of genotype composition, rapid multiplication of shoots or roots, production of material free of viruses and/or other contaminants, and easier collection, storage, and transportation. Culture of apical meristems, the induction of axillary and adventitious shoots and regeneration by somatic embryogenesis and organogenesis are common micropropagation techniques allowing stable and homogeneous material to be obtained on a large scale. Due to the numerous advantages of micropropagation and *in vitro* plant tissue culture it is also an efficient and cost-effective technique for the biosynthesis, biotransformation or bioconversion of compounds of plant origin (used in biofarming already described above).[24] Hydroponic techniques, such as deep water culture (plant seeds are sown in an inert medium floating on a deep tank of circulating water or nutrient solution, where roots develop in search of food) and nutrient film techniques (nutrient solution delivered continuously in a shallow, recirculating stream through an inclined growth tray where the roots are minimally submerged, which improves aeration of the root zone and has a positive impact on plant development), are very efficient in terms of water use, but are quite costly in terms of equipment, energy and space. Aquaponic systems are characterised by the simultaneous cultivation of both fish (aquaculture) and plants (hydroponics). They use the conversion of fish waste into food for plants by naturally occurring microbiota, followed by recultivation and recirculation of the water consumed by plants (see Chapter 8). These systems are highly efficient from the point of view of consumption of water and nutrients, though they do require constant monitoring and adaptation of the nutrient composition due to the nutritional requirements of fish, bacteria of the system microbiota and plants.[25] Aeroponic methods consist of providing nutrients in the form of aerosol droplets (10–100 μm) using various atomisation techniques. Their indisputable advantage is to offer the highest water efficiency of all soilless cultivation methods and excellent root zone aeration. In this case, the disadvantages are sophisticated instrumentation, susceptibility to power outages, or suboptimal nutrient formulations.[26] Vertical farming involves plant cultivation in vertically stacked irrigation systems, using artificial or natural light. The main cultivation methods in vertical farming are hydroponics or

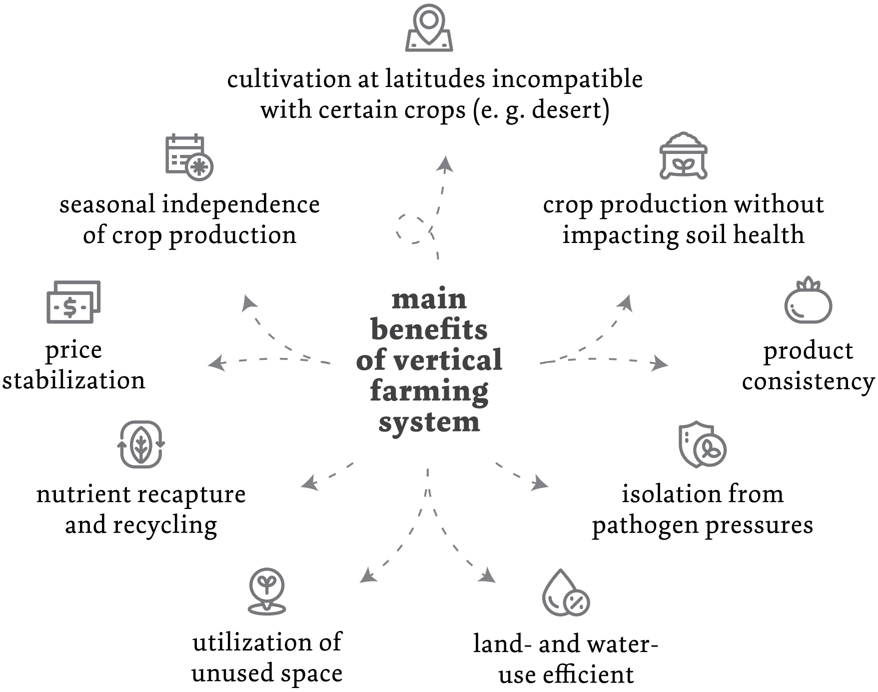


Figure 10.3 Advantages of vertical farming.

Source: Own elaboration.

aeroponics already discussed above. Vertical systems have been developed in response to the need for urban food production (urban farming), and policy to reduce the share of transport in food-supply chains.[27] Significant advantages of vertical farming are shown in Figure 10.3.

The potential benefits and value that vertical farming brings to the bioeconomy are undeniable and closely related to sustainable development goals. Market research suggests that the vertical farming sector is expected to grow by over 20% annually in the years to come to reach an estimated value of $9.96 billion by 2025.[28]

10.2.2 Animal biotechnology

Animal products, such as meat, milk, eggs and fish, are important components of the human diet, which is why, for many years, breeders have been trying in traditional ways to improve breeds of animals (mainly through crossbreeding) to obtain the best results. Crossbreeding combines two sexually compatible species, creating a new valuable variety with the desired characteristics of the parents. Examples include new breeds of animals with more meat, giving more milk with high fat content, laying more eggs. A scientific breakthrough in the field came when the first GM mouse was bred. Since then, GM mice have been an indispensable part of medical research, serving as also human disease models.[29] Although this does not have a direct impact on the bioeconomy, it is helping to change the perception of the value of GM animals for the quality of our lives. Currently, most GM animals are used in red biotechnology related to medicine – not only for model-based research but also for the production of substances important in the therapy of human diseases (e.g. insulin, medicinal proteins). There are also GM animals with potential for use in xenotransplantation. Breeding GM animals is a big step forward in animal biotechnology, but too many unknowns mean that widespread commercialisation of these animals will not occur in the coming years. In 2015, the United States Food and Drug Administration (US FDA) gave its first approval to sell AquAdvantage GM salmon to consumers which was modified for a faster growth rate. In 2020, the US FDA also approved the use of genetically modified GalSafe GM pigs in both food and medical products. These GM pigs can be used to produce medicines, provide organs and tissues for human transplants, and produce meat that is safe to eat for people with meat allergies.[30] It must be emphasised that more than 95% of animals used for meat and dairy in the United States eat GM crops, but GM foods do not affect the health and safety of animals[31] and these animals are not classified as GM.

10.2.3 Bioproducts

The increased interest in "healthy food" has led many agri-food research and biocontrol technologies to search for natural substances and microorganisms that promote the growth of crop plants or can be used in biological plant protection and weed control. Currently, numerous initiatives are being undertaken to reduce the use of chemicals while limiting the negative side effects of their use in agriculture. In the years to come, both agricultural science and practice will have to devote a lot of attention and effort to the development and implementation of integrated crop protection methods. With regard to the agro market, in many countries we can find preparations originating from a living organism or its products (biologically based agents) which can be used as biopesticides and biofertilisers, as well as selected cultures of microorganisms for soil remediation and composting.

The term *biological control* was first used by Harry Scott Smith in 1919. It relies on predation, parasitism, herbivory or other natural mechanisms, but typically also involves an active human management role. There are three basic strategies for biological pest control: classical (importation), where a natural enemy of a pest is introduced in the hope of achieving control; inductive (augmentation), in which a large population of natural enemies are administered for quick pest control; and inoculative (conservation), in which measures are taken to maintain natural enemies through regular reestablishment.[32] According to the United States Environmental Protection Agency,[33] the major classes of biopesticides are:

- biochemical pesticides – naturally occurring substances that control pests by non-toxic mechanisms: include substances that interfere with mating, such as insect sex pheromones, as well as various scented plant extracts that attract insect pests to traps (examples in Table 10.2),
- microbial pesticides – consisting of a microorganism (bacteria, fungi) and viruses as the active ingredient; each specific to the target pests (e.g. entomopathogenic fungi, *B. thuringiensis* producing *Cry* toxic proteins) (examples in Table 10.2),
- Plant-Incorporated-Protectants (PIPs) – pesticidal substances that plants produce from genetic material that has been added to the plant (e.g. Bt maize).

Biopesticides are inherently less toxic than conventional pesticides. They are often very specific, effective in very small quantities, compatible with other control agents and leave little or no residue. However, they have lower potency than synthetic pesticides. Biological plant protection is still not used extensively due to high competition from chemical plant protection product, variable effectiveness depending on environmental conditions, plant species or variety, and the relatively small number of registered biopreparations. Successfully implementing a biological control programme requires an understanding of the pests, natural enemies, the environment, and the interactions of all factors. Despite difficulties in adoption, biological control and Integrated Pest Management (IPM) can provide benefits that contribute to building a sustainable environment and increasing profitability by reducing management overhead.

Macroorganisms form a separate group of biological plant protection agents. The effective protection against pests using their natural enemies (referred to as macroorganisms despite their rather microscopic dimensions) was first reported in England in 1927. At the time, a *Encarsia formosa* wasp parasitising the greenhouse whitefly was used in tomato cultivation. In 1960, a predator of spider mites – the *Phytoseiulus persimilis* predatory mite – was discovered in Germany on orchids imported from Chile. A technology to breed them was developed quite quickly. To this day, these two historic examples remain methods of biological protection used in pest control with the use of "macroorganisms". Currently, beneficials mites and Trichogramma wasps (parasitoids of lepidopteran eggs, such as European corn borers) are of practical importance globally. Another interesting group of macroorganisms are insecticidal nematodes. In practice, two genera of nematodes, Steinernema and Heterorhabditis, are used in bioinsecticides. These are soil nematodes which look for host insects and enter them through natural openings in the body. Once inside the haemocoel, the nematodes release *Xenorhabdus* and *Photorhabdus* bacteria, with which they live in a mutualistic relationship. The bacteria multiply and secrete a range of toxins and hydrolytic enzymes that are responsible for the death of the insects within 24 to 48 hours. Steinernema and Heterorhabditis have a very wide range of hosts among pests of economic importance and are environmentally safe.[36]

Table 10.2 Commercially important examples of plant compounds, microorganisms and viruses used as biopesticides and their applications[34,35]

Group	*Example*	*Mode of action*
biochemical insecticides – plant compounds	azadirachtin	insect growth regulator, interfering with the development in preimaginal stages; inhibits the formation and secretion of ecdysone, has an effect on the hormonal level, causing morphogenetic disorders, leading to the formation of what are referred to as "permanent" larvae; has a repellent effect resulting from a gustatory, olfactory and neurophysiological effect, causes a significant decrease in the egg-laying activity and the viability of eggs; also limits the growth of fungi
	pyrethrins	in contact rapidly attacks the nervous system of insects; pests lose the ability to coordinate movements and gradually become paralysed, short-term toxicity, synergising ingredients are usually added to commercially available preparations, which increases the effectiveness thus blocking the system responsible for detoxification
microbial insecticides –bacteria	*Bacillus thuringiensis*	pathogenicity is determined by the action of Cry and Cyt crystalline toxins, which cause structural loosening and perforation of guts, leading to the digestive system or general paralysis, pests stops feeding and dies, these toxins also disturb the functioning of the nervous system through changes in ion exchange
	Lysinibacillus (Bacillus) sphaericus	binary toxin protein: bina + binb bound to specific receptors of the intestinal epithelium of the stomach and midgut, causing perforation, which leads to disruption of the osmotic balance, cell lysis, and ultimately death of the insect
	Serratia entomophila	bacterium releases toxins after ingestion by the insect, resulting in the cessation of food intake, emptying of the intestine and retention of digestive enzymes in the stomach, infected larvae take on a characteristic amber colour
microbial insecticides –fungi	*Beauveria bassiana* *Isaria fumosorosea* *Metarhizium anisopliae*	infections caused by all species of entomopathogenic fungi follow a typical course for a fungal disease initiated by adhesion, spore germination and mycelial overgrowth through the cuticle into the haemocoel, which results in the death of the host

(*Continued*)

Table 10.2 (Continued)

Group	*Example*	*Mode of action*
microbial fungicides –fungi	*Trichoderma* spp.	limit the development of other fungi (including phytopathogenic fungi) through hyperparasitism, competition and antibiosis
virus insecticides	*Cydia pomonella* granulosis Virus (CpGV)	once the virus is in the host cell, its nucleic acid takes control of the cell's metabolic system and virus particles start to replicate, leading to cell death

The control of pests is not the only possible positive impact on obtained yields. For several decades now, one particularly intensive area research has been stimulation of plant growth and immunity. Plants never exist in isolation – they always interact with environmental components. The plant-microbiome or phytomicrobiome plays a crucial role in plant health and yield by modulating the production of phytohormones, improving root development, increasing the availability nutrients and resistance against pests and mitigating biotic and abiotic stresses. Rhizosphere fungal and bacterial communities that have a beneficial effect on plants are called Plant Growth-Promoting Microbes (if fungi PGPFs, if rhizobacteria PGPRs). Bacteria can fix nitrogen (symbiotic and free-living N2 fixers), convert insoluble soil phosphorus into plant-available forms through various mechanisms of solubilisation and mineralisation, as well as solubilise potassium, oxidise sulphur, or solubilise or chelate micronutrients and facilitate the production of siderophores enhancing iron update – thus acting as biofertilisers. Also root mycorrhizal fungi play a special role because they can form symbiotic relationships with ~80% of land plant species. The best-studied plants–fungi symbiosis refers to obligate, arbuscular mycorrhizal fungi (AMF) of the Glomeromycota phylum. These fungi contribute to nutrient mobilisation, increasing the uptake of minerals (i.e. P, N, S, Cu and Zn) and water by host plants. Generally biofertilisers can be defined as preparations containing living microorganisms (single strains or consortia) that promote plant growth by increasing the availability and acquisition of nutrients. Microbial fertilisers are considered key elements of sustainable agriculture, having a long-term impact on soil fertility.[37] Another group of such preparations based on raw materials of natural origin, which can be amino acids, protein hydrolysates, humic substances, macro or microalgae, chitosan and other biopolymers are called plant biostimulators. Biostimulators are used in very small quantities and improve plant growth by stimulating direct or indirect release of phytohormones.[38]

The wide range of bioproducts discussed meets all the requirements for sustainable agricultural means of production and allows modern requirements of the bioeconomy to be fulfilled in the area of primary production. The application of bioproducts can prevent the excessive use of synthetic chemical means of production. Of course, bioproducts implemented in practice should be tested and meet all safety requirements while complying with the applicable standards for all substances or organisms introduced into the environment. Bioproducts are already an important part of integrated and ecological plant production! One very optimistic piece of information is, that based on research conducted on the pesticides market, it is expected that biological protection will become the main method of crop protection by 2030, and the share of biopesticides in the global market for plant protection agents will be over 50%. Other bioproducts, namely biofertilisers and biostimulants, are also an important sector in innovative means of production, and the development of this sector will be even more dynamic due to the less restrictive process of registration for this type of substance. Sustainable, integrated or ecological plant production, including biological protection, natural fertilisation and biostimulation of crop plants, is the only way forward for global agriculture, which will have to meet the challenges facing the global bioeconomy.

10.3 White biotechnology

The next branch of biotechnology essential to the bioeconomy, termed white biotechnology, stands at the confluence of nature and industry. White biotechnology refers to the use of living cells and enzymes to synthesise products that are traditionally produced through industrial methods. This covers a range of products from biofuels and chemicals to bioplastics. White biotechnology offers a greener alternative to conventional manufacturing processes. By utilising renewable raw materials and minimising waste through biotransformation processes, white biotechnology aligns industrial production with environmental responsibility and often results in reduced energy consumption and increased efficiency, what make it economically viable. The advancement of white biotechnology is critical to expanding the bioeconomy and the circular economy. At the heart of this sector of biotechnology lie the microscopic powerhouses – bacteria, fungi, and yeast with unique metabolic capabilities – that drive the synthesis of a multitude of products, have positioned themselves as indispensable assets in this sector (Figure 10.4). Figure 10.4 shows the systematic conversion of diverse input feedstocks, such as agricultural-derived sugars, various gases, and lignocellulosic biomass, into an assortment of chemical products with the central role of biotransformation mechanisms, including fermentation processes utilising microorganisms, along with cell-free systems. The resulting products are a spectrum of industrially significant compounds ranging from basic organic acids to complex molecules like diols, alcohols, diamines, as well as isoprene, terpenes, hydrocarbons, and a variety of other organic compounds.

Bacteria (unicellular prokaryotic microorganisms) are versatile in biotechnological applications.[39] The most renowned, *Escherichia coli*, has been genetically engineered in countless ways to produce biofuels, pharmaceuticals, and even specialty chemicals. Beyond *E. coli*, other species from the *Bacillus* and *Corynebacterium* genus have become useful in enzyme production and amino acid synthesis, respectively. Also fungi, especially filamentous, are famous for

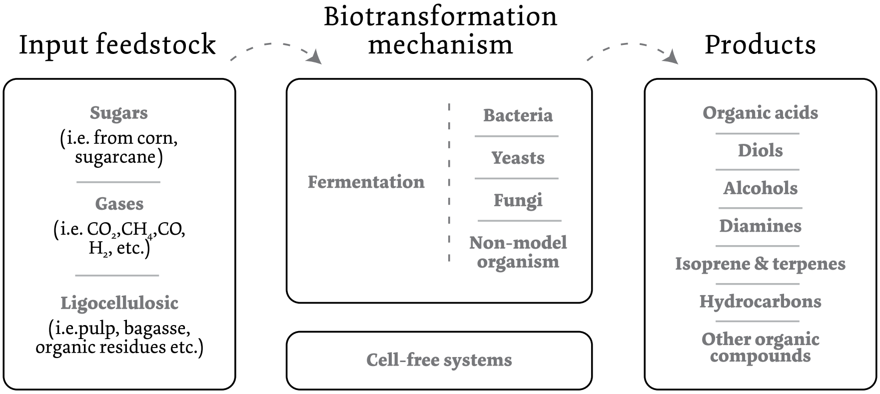


Figure 10.4 Comprehensive overview of white biotechnology processes.

Source: Own elaboration based on: IDTechEx, https://www.idtechex.com.

their ability to produce a plethora of enzymes and molecules, and unique to this group antibiotics. Their inherent capability to degrade complex substrates has led to their widespread use in food, paper and textiles productions. *Aspergillus niger*, for instance, is a chief producer of citric acid – an additive ubiquitously found in foods and beverages. *Saccharomyces cerevisiae* yeast, having been used for millennia in bread-making and alcohol fermentation, in modern industrial biotechnology, its applications have been expanded. GM yeasts are now instrumental in producing bio-based chemicals. The power of these microorganisms lies not just in their ability to reproduce rapidly or their flexibility to genetic manipulation but also, and predominantly, in their vast and diverse metabolic pathways. The relevance of this metabolic versatility is profound. Different industries have distinct requirements. The pharmaceutical industry might require a specific chiral compound; the biofuel sector might need efficient conversion of biomass to ethanol, and the food industry could be after a specific flavouring agent. With metabolic engineering, yeasts can be tailored to fit these niche requirements, optimising the desired pathway to enhance yield, purity or efficiency. Furthermore, the metabolic diversity serves as a treasure trove for discovering novel compounds. Synthetic biology, a burgeoning field, takes research beyond mere tinkering with existing metabolic pathways; it aspires to design and construct entirely new biological systems. By rewriting the genetic code, introducing synthetic DNA, or even creating minimalistic genomes tailored for specific tasks, synthetic biology can generate micro-factories with unprecedented capabilities often achieve unparalleled production yields.

Every biological process, from digestion to DNA replication, hinges on enzymes. These proteins have a unique ability: they can speed up chemical reactions without themselves being consumed. This catalytic power is attributed to their intricate structure, particularly an active site that binds specific molecules, or substrates, and aids in their transformation. Their action is akin to fitting a key into a lock, where only the right key (substrate) fits perfectly, ensuring high specificity and reduced unwanted side reactions. It is essential to note that these enzymes are often produced by microbes, a core facet of white biotechnology, through either natural strains or GMOs. The industrial application of enzymes is vast and varied.[40] Proteases have become mainstays in laundry detergents. They break down protein-based stains (e.g. blood, grass), allowing for effective cleaning even at lower temperatures. Lipases and amylases are used to target fat and starch stains, respectively. A groundbreaking application of lipases is in the chiral synthesis of biopharmaceuticals. In non-aqueous solvents, lipases can selectively act on specific isomers, enabling the synthesis of chiral compounds vital for drug development. This specificity is crucial because different isomers, or enantiomers, of a drug molecule can have vastly different therapeutic effects. The textile industry employs enzymes in processes like desizing and biopolishing. Cellulases are used to give denim its faded look without the use of harsh chemicals or abrasive stones. Enzymes play vital roles in food processing: amylases are used in baking to break down starches, improving the texture of bread; in the brewing industry they help in breaking down grains to release fermentable sugars; rennet, a mixture containing chymosin, is traditionally used in cheese production to coagulate milk. Enzymes also find a wide range of applications in the paper industry, biofuel production, waste treatment and pharmaceutical manufacturing. Enzyme engineering, using techniques like directed evolution or rational design, can modify structures to improve stability, specificity, or activity. For instance, an enzyme that is naturally sensitive to heat can be engineered to function optimally in the high-temperature conditions of an industrial process. Immobilisation techniques have also revolutionised enzyme technology. By attaching enzymes to solid supports or entrapping them in gels or matrices, they can be reused multiple times, enhancing process efficiency and reducing costs. Immobilised enzymes also offer easier product separation and enable continuous processing.

10.3.1 Bio-based chemicals

Organic acids, notably citric, lactic, and acetic acids, have been traditionally sourced from chemical processes. However, microbial fermentation offers a greener and often more efficient alternative. For instance, *A. niger* is employed to ferment sugars into citric acid, a critical industrial chemical with applications ranging from food and beverages to pharmaceuticals. Similarly, many strains of *Lactobacillaceae* are able to convert carbohydrates into lactic acid, which can be used as a food preservative but more notably as a precursor for bioplastics – polylactides. Amino acids, the building blocks of proteins, have also seen a shift towards microbial production. Lysine and glutamic acid, vital for human nutrition and widely used in the food industry, are now predominantly produced by fermenting specific strains of *Corynebacterium glutamicum*. The advantages include higher yields, reduced costs, and enhanced purity compared to chemical syntheses or extraction from protein hydrolysates. Vitamins, essential micronutrients, have also benefited from biotechnological interventions. For instance, Vitamin B2 (riboflavin) production was conventionally based on chemical synthesis. Today, fermentative production using microbes like *Ashbya gossypii, B. subtilis*, and *Candida* spp. has become a leading method due to its efficiency and reduced environmental footprint.

The pharmaceutical industry is constantly seeking new and effective compounds, with natural sources frequently serving as primary candidates. However, direct extraction of these compounds from plants or animals can be resource-intensive, expensive, and occasionally raise ethical concerns. Biotechnology offers a solution by facilitating the microbial synthesis of these crucial compounds. Penicillin, the pioneer antibiotic, provided an early example of this. While originally extracted from the fungus *Penicillium*, advances in biotechnology have optimised strains for enhanced production levels. Another striking example is the production of artemisinin, an antimalarial drug. Traditionally, this has been sourced from the sweet wormwood plant. Through synthetic biology, a yeast strain was engineered to produce artemisinic acid, a precursor to artemisinin, ensuring a consistent and scalable supply. Furthermore, microbes can be harnessed to produce precursors for synthesising complex drugs, reducing the steps and resources required in traditional chemical synthesis. With combination of theoretical modelling and artificial intelligence this approach not only ensures a more sustainable and scalable production method but can also lead to derivatives of the original molecule, potentially yielding drugs with enhanced efficacy or reduced side effects.

10.3.2 Biofuels and bioenergy

The ever-growing demand for energy, coupled with the detrimental environmental impacts of fossil fuels, has driven the global quest for alternative, sustainable energy sources.[41] Biofuels and bioenergy stand at the forefront of this pursuit, offering renewable energy options derived from biological materials. First-generation biofuels are derived from sugars, starches and vegetable oils. These feedstocks are usually food crops like corn, sugarcane and soybean. The biofuels produced include ethanol (from fermented sugars and starches) and biodiesel (from vegetable oils and animal fats). While they provide a cleaner-burning alternative to fossil fuels, the primary criticism of first-generation biofuels lies in the competition with food supply. Using agricultural crops for energy production raises concerns about food security and potential implications for food prices. Nevertheless, bioethanol and biodiesel, as sustainable alternatives to fossil fuels, play important roles in the evolution of renewable energy sources for transportation. Bioethanol is an alcohol primarily derived from the fermentation of sugars present in crops like sugarcane, corn and beet. When used as a fuel, it can be blended with gasoline to produce a mix suitable for vehicle engines. The use of bioethanol offers several advantages. First, it is renewable, being derived from plants that can be cultivated annually. Second, it has a cleaner combustion profile, leading to reduced greenhouse gas emissions compared to pure gasoline. Biodiesel, on the other hand, is derived from vegetable oils, animal fats or even used cooking oil. It can replace or be blended with conventional diesel fuel. The transesterification process converts these oils and fats into biodiesel and glycerin. Biodiesel offers a reduction in carbon emissions and is biodegradable, reducing environmental risks in cases of spills. Moreover, it provides an avenue for recycling used cooking oils. Like bioethanol, the sustainability of biodiesel depends on its feedstock, pushing research towards non-food sources like algae or waste materials. Second-generation biofuels, on the other hand, are produced from non-food biomass sources. This includes agricultural residues (like straw and husks), forest residues, and specially cultivated energy crops. These materials are primarily composed of lignocellulosic fibres, which, being tougher to break down, can be converted to biofuels like cellulosic ethanol. The advantage here is the reduction in competition with food crops and, often, a better overall carbon footprint due to the full utilisation of plant materials. There are many examples of the second-generation energy sources; however, two are notably the most promising – algal biofuels and biomethane. Algae, given their rapid growth rate and high oil content, are emerging as a promising feedstock for biofuel production. Algal biofuels do not compete with arable land meant for food crops. Moreover, algae can be cultivated in various environments, including saline water, reducing the strain on freshwater resources. Once harvested, the lipids from the algae are extracted and converted into biodiesel, while the remaining biomass can be used for other applications, further maximising resource utilisation. Biogas primarily consists of methane and carbon dioxide and is produced through the anaerobic digestion of organic materials. This includes any organic waste available. Once produced, biogas can be used directly for heating or electricity generation. Biomethane is the purified form of biogas, where the carbon dioxide and other impurities are removed, resulting in a higher methane concentration. It possesses similar characteristics to natural gas and can be injected into the gas grid or used as a transport fuel. In essence, biofuels and bioenergy offer promising alternatives to our reliance on fossil fuels. As research continues and technologies mature, it is expected that biofuels and bioenergy will play an even more significant role in our global energy landscape.

10.3.3 Biomaterials and biopolymers

As our understanding of biological systems advances and intertwines with materials science, a new epoch of materials – biomaterials and biopolymers – emerges.[42] These materials, either derived from nature or inspired by it, not only promise reduced environmental impact but also boast properties that can be tailored for specific applications, from packaging to advanced healthcare. The global concern about plastic waste, especially its persistence in the environment, has accelerated research into biodegradable polymers. Unlike conventional plastics derived from petrochemical sources, biodegradable polymers break down into harmless components under natural conditions, alleviating concerns about long-term environmental contamination. Polyhydroxyalkanoates (PHAs) and polylactic acid (PLA) are prime examples. PHAs are produced by bacteria under nutrient-limited conditions and are fully biodegradable. Depending on the bacterial strain and cultivation conditions, PHAs can have properties ranging from being elastomeric to highly crystalline, making them suitable for a variety of applications. PLA, derived from the fermentation of plant sugars to lactic acid, is another leading biopolymer. It is processed in a similar way to petrochemical-based plastics, but, upon disposal, it can be composted, breaking down into its monomers, a naturally occurring compound – lactic acid. The allure of these materials is not just their biodegradability but also their origin: renewable resources, often agricultural by-products or waste, ensuring a lower carbon footprint than their petrochemical counterparts.[43]

10.3.4 Bioprocess engineering

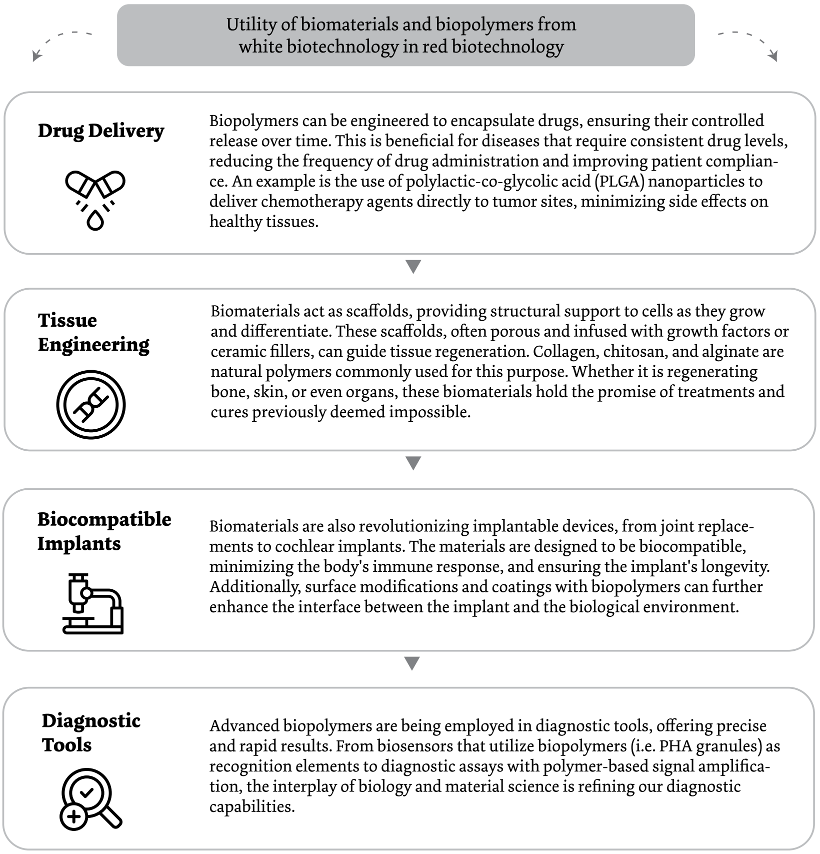
Bioprocess engineering that encompasses the principles and practices required to translate the discoveries of life sciences into tangible products, especially through the use of living cells or their components constitutes an important aspect in white biotechnology.[44] Central to this field is the ability to harness biological systems for the production of goods spanning from biofuels to therapeutics. Key aspects include designing and optimising fermentation processes, bioreactor configurations and downstream processing techniques. Table 10.3 presents the types of fermentation used in biotechnology.

Case study

The use of white biotechnology in an application related to red biotechnology – functional materials for medical applications

Despite the division of biotechnology, all its colour branches create a complementary network. Many technologies of a given branch find applications in others, resulting in the great impact that has biotechnology on and the contribution it makes to the sustainable development of the bioeconomy and other areas of our lives. A case study is provided as an example of the flow between branches of biotechnology.

Within the medical realm, the utility of biomaterials and biopolymers exceeds mere biodegradability. The convergence of biotechnology and materials science is generating materials with functionalities tailored for sophisticated medical applications. Figure 10.5 summarises the use of white biotechnology-derived biomaterials in drug delivery, tissue engineering, biocompatible implants, and diagnostic tools. It emphasises their role in controlled drug release, scaffold-based tissue regeneration, enhanced compatibility of medical implants and the advancement of diagnostic technologies.



Utility of biomaterials and biopolymers from white biotechnology in red biotechnology

Drug Delivery

Biopolymers can be engineered to encapsulate drugs, ensuring their controlled release over time. This is beneficial for diseases that require consistent drug levels, reducing the frequency of drug administration and improving patient compliance. An example is the use of polylactic-co-glycolic acid (PLGA) nanoparticles to deliver chemotherapy agents directly to tumor sites, minimizing side effects on healthy tissues.

Tissue Engineering

Biomaterials act as scaffolds, providing structural support to cells as they grow and differentiate. These scaffolds, often porous and infused with growth factors or ceramic fillers, can guide tissue regeneration. Collagen, chitosan, and alginate are natural polymers commonly used for this purpose. Whether it is regenerating bone, skin, or even organs, these biomaterials hold the promise of treatments and cures previously deemed impossible.

Biocompatible Implants

Biomaterials are also revolutionizing implantable devices, from joint replacements to cochlear implants. The materials are designed to be biocompatible, minimizing the body's immune response, and ensuring the implant's longevity. Additionally, surface modifications and coatings with biopolymers can further enhance the interface between the implant and the biological environment.

Diagnostic Tools

Advanced biopolymers are being employed in diagnostic tools, offering precise and rapid results. From biosensors that utilize biopolymers (i.e. PHA granules) as recognition elements to diagnostic assays with polymer-based signal amplification, the interplay of biology and material science is refining our diagnostic capabilities.

Figure 10.5 Applications of biomaterials and biopolymers in red biotechnology.

Source: Own elaboration.

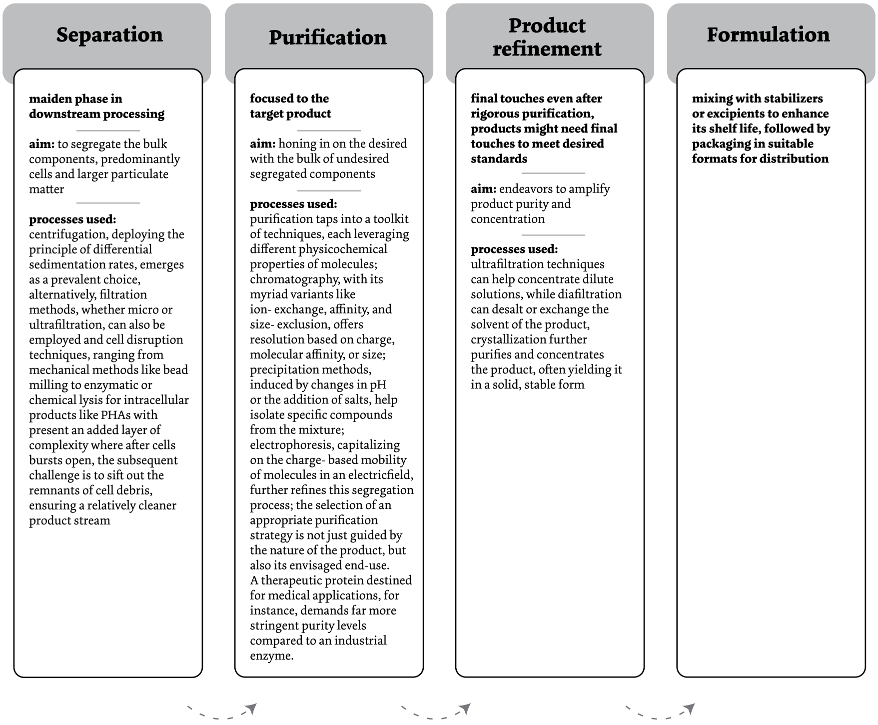
Bioreactors stand as the core elements in bioprocessing, serving as meticulously designed chambers wherein biological reactions unfold under carefully modulated conditions. These essential vessels, conceptualised to foster life, are moulded based on factors such as the organism in focus, the targeted end-product, and the anticipated operational scale. The basic variants of bioreactors are: stirred-tank bioreactors, airlift bioreactors, packed-bed bioreactors and fluidised-bed bioreactors. Stirred-tank bioreactors are the workhorses of both microbial and mammalian cell culture processes. Their inherent design incorporates impellers that facilitate thorough mixing, ensuring that nutrients, oxygen, and the cultured cells are uniformly dispersed throughout the liquid medium. Such an even distribution promotes consistent growth conditions, enabling reproducible outcomes. The versatility of these bioreactors, combined

Table 10.3 Characteristics of fermentation processes used in white biotechnology

Type of fermentation	*Characteristic*
Batch	Begins with the introduction of all essential nutrients into the bioreactor. From this point, the fermentation progresses autonomously without any subsequent input or extraction of materials until its conclusion. This approach is particularly appropriate for the production of biomass or for products that emerge during growth-associated phases. Nonetheless, it has intrinsic limitations. Over time, there is a tangible risk of nutrients being exhausted and the accumulation of waste, which might inhibit the fermentation process.
Fed-batch	Adopts a more controlled approach, involves the periodic or slow and steady addition of nutrients to the bioreactor. This strategic supplementation ensures that microbial growth and productivity are sustained over a prolonged period. By preventing the complete exhaustion of nutrients and averting excessive waste accumulation, fed-batch processes can enhance the yield of the target product. This mode is especially efficacious for the production of compounds that are synthesised during non-growth linked phases.
Continuous	Perpetual introduction of fresh medium into the bioreactor. In tandem, an equivalent volume of the spent medium – laden with products, residual cells, and unused substrates – is systematically evacuated. This continuous exchange stabilises the operational conditions within the bioreactor, ensuring a consistent cell density and a steady rate of product formation. When scalability and uniformity in production are paramount, especially for growth-associated products, continuous fermentation emerges as the method of choice.

with the ease of scalability, renders them a preferred choice for many industrial applications. Airlift bioreactors are distinguished by their reliance on air to facilitate mixing and oxygenation, and are tailored for cultures that demand gentler handling. The absence of mechanical agitators means there is reduced shear stress, making them particularly apt for cultivating fragile cells, including certain microalgae and plant cells. Given their design, these bioreactors are often used for large-scale biomass production, especially when dealing with photosynthetic organisms that benefit from light exposure. At the core of packed-bed bioreactors lies a fixed bed, densely packed with immobilised cells or enzymes. As the culture medium meanders through this packed matrix, it interacts intimately with the immobilised biological entities, leading to efficient conversion processes. One of the hallmarks of packed-bed bioreactors is their resilience, especially when the production environment contains compounds that are detrimental to the cells. The immobilised cells, protected in their fixed state, often showcase enhanced resistance to toxicants, ensuring uninterrupted production. In dynamic fluidised-bed bioreactors, cells find themselves anchored to minuscule carrier particles. When the culture medium is introduced with an upward thrust, these particles (along with the attached cells) get fluidised, creating an environment that blends the merits of both stirred-tank and packed-bed bioreactors. The resulting setup encourages excellent mixing and elevated rates of mass transfer. Moreover, the constant movement minimises cell clumping and fosters a uniform exposure to nutrients and oxygen.

At the culmination of fermentation or any bio-based production process, the sought-after product often finds itself submerged in a diverse milieu of cells, residual substrates, and a spectrum of metabolites. The journey of retrieving and refining this product from this intricate web is encapsulated in the downstream-processing realm as illustrated in Figure 10.6, where stages of bioproduct processing such as separation, where cells and larger particulate matter are isolated; purification, focusing on the extraction of desired molecular components; product refinement ensuring the product meets rigorous quality standards; formulation describes the integration of stabilisers and packaging, crucial for the product's shelf life and distribution readiness are presented.



Separation

maiden phase in downstream processing

aim: to segregate the bulk components, predominantly cells and larger particulate matter

processes used: centrifugation, deploying the principle of differential sedimentation rates, emerges as a prevalent choice, alternatively, filtration methods, whether micro or ultrafiltration, can also be employed and cell disruption techniques, ranging from mechanical methods like bead milling to enzymatic or chemical lysis for intracellular products like PHAs with present an added layer of complexity where after cells bursts open, the subsequent challenge is to sift out the remnants of cell debris, ensuring a relatively cleaner product stream

Purification

focused to the target product

aim: honing in on the desired with the bulk of undesired segregated components

processes used: purification taps into a toolkit of techniques, each leveraging different physicochemical properties of molecules; chromatography, with its myriad variants like ion- exchange, affinity, and size- exclusion, offers resolution based on charge, molecular affinity, or size; precipitation methods, induced by changes in pH or the addition of salts, help isolate specific compounds from the mixture; electrophoresis, capitalizing on the charge- based mobility of molecules in an electricfield, further refines this segregation process; the selection of an appropriate purification strategy is not just guided by the nature of the product, but also its envisaged end-use. A therapeutic protein destined for medical applications, for instance, demands far more stringent purity levels compared to an industrial enzyme.

Product refinement

final touches even after rigorous purification, products might need final touches to meet desired standards

aim: endeavors to amplify product purity and concentration

processes used: ultrafiltration techniques can help concentrate dilute solutions, while diafiltration can desalt or exchange the solvent of the product, crystallization further purifies and concentrates the product, often yielding it in a solid, stable form

Formulation

mixing with stabilizers or excipients to enhance its shelf life, followed by packaging in suitable formats for distribution

Figure 10.6 Stages of bioproduct processing.

Source: Own elaboration.

10.3.5 Biorefineries – the future of sustainable production

In a world biorefineries emerge as the cornerstones of sustainable production, bridging the gap between renewable resources and our ever-growing demands for energy, materials, and chemicals.[45] They represent not just an industrial facility, but a paradigm shift, echoing the holistic principles of traditional refineries but with an emphasis on green, renewable sources. Just as petroleum refineries process crude oil into a plethora of valuable products ranging from gasoline to plastics, a biorefinery processes biological raw materials, primarily biomass, into a variety of bio-based products and bioenergy. The core principle underscoring biorefineries is their multi-product approach: extracting maximum value by converting biomass components into a spectrum of marketable products, be it biofuels, biochemicals, or biomaterials. Their use of biomass – a renewable and often locally available resource – reduces dependency on fossil raw materials, curbing greenhouse gas emissions in the process. Biomass is a complex assembly of carbohydrates (such as cellulose and hemicellulose), lignin, proteins, and lipids. The skill of the biorefinery revolves around deconstructing this intricate network into valuable products. For instance, cellulose and hemicellulose can be degraded into fermentable sugars via hydrolysis. These sugars then act as primary feedstocks for the microbial fermentation of bioethanol or other bio-based compounds. Lignin, which is frequently viewed as a residue in many bioconversion routines, is gaining attention for its potential in producing valuable products like bioplastics, resins and carbon fibres. Additionally, abundant lipids and oils in sources like algae or seeds are processed into biodiesel or other significant chemicals using methods such as transesterification. The hallmark of an efficient biorefinery is its integrated approach, where the aim is to harness every fragment of the biomass. This philosophy echoes nature's zero-waste principle, ensuring that what might be deemed 'waste' in one process becomes 'feedstock' in another. For instance, the residual biomass post biofuel production, often rich in proteins, can be channelled as animal feed. The lignin, once stripped of its polysaccharides, can be valorised into myriad products or even combusted to generate energy that can power the biorefinery, closing the loop in the process. This integrated, circular approach underscores the efficiency of biorefineries, ensuring economic viability. Whether it is through genetically modified organisms tailored to enhance bioconversion efficiency or novel catalysts that speed up reactions, the world of biorefineries is ever-evolving, ever-optimising. By reimagining the way we produce, by replacing the finite with the renewable, and by integrating processes to extract maximal value with minimal waste, biorefineries embody the synergy of nature and technology.

Case study

Circular biorefinery – transforming cellulosic sugars to bio-based products

In an era where sustainability and resource efficiency are paramount, the conceptualisation of a biorefinery that not only produces a primary product but also channels its by-products into further value-added outputs is revolutionary. The following case study delves into a unique biorefinery model that champions the principles of the circular bioeconomy, using cellulosic sugars as a cornerstone. This biorefinery model demonstrates a circular bioeconomy approach. Utilising sugars from cellulose, it produces a biopolymer and efficiently uses all by-products, including spent medium and post-catalysis solvents, for further value-added production. By closing the loop, this model offers a blueprint for future biorefineries, underscoring the principles of sustainability, innovation, and efficiency (Figure 10.7).

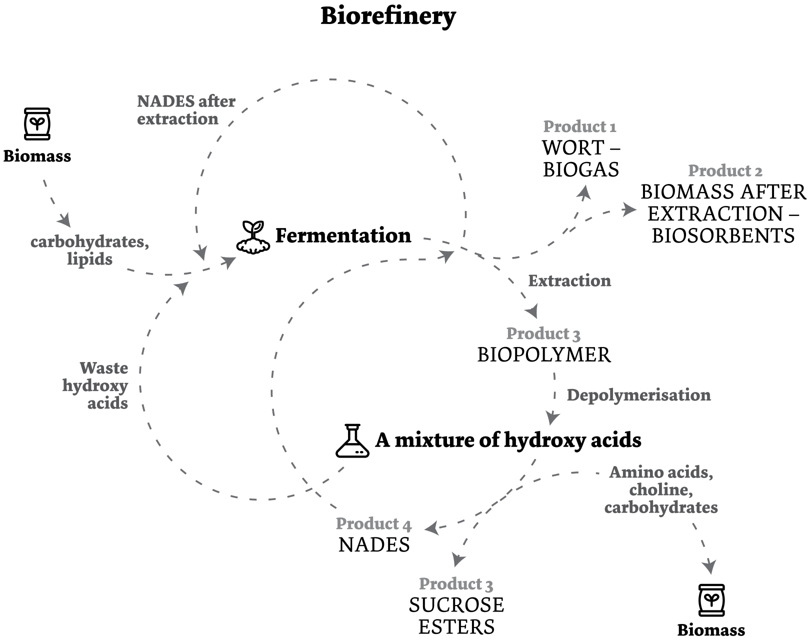


Figure 10.7 Biorefinery process diagram: circular economy from plant inputs to reusable products.

Source: Own elaboration.

Description of phases

Phase 1: Production of biopolymer and fertilisers

Input: Sugars derived from the biodegradation of cellulose, an abundant bioresource. Process: Fermentative production of Polyhydroxyalkanoates (PHA). *Outputs*: primary product – PHA, a biopolymer with myriad applications ranging from medical to environmental solutions due to its biodegradability and biocompatibility; by-products – Post-fermentation spent medium and bacterial biomass after extraction of PHA. Both serve as valuable organic fertilisers, rich in nutrients and minerals.

Phase 2: Valorisation of the biopolymer
Direct utilisation: PHA, in its polymer form, can be directly utilised in various applications. For instance, its biocompatibility makes it a coveted material for medical applications, from sutures to drug delivery systems. Depolymerisation: PHA can be further processed to break it down into its constituent monomers, specifically 3-hydroxyacids. *Synthesis of green solvents*: The derived 3-hydroxyacids can be integrated with other biomolecules, like choline chloride, to fabricate Deep Eutectic Solvents (DESs). These solvents, known for their eco-friendliness, serve as potent mediums for catalysis.

Phase 3: Creation of platform chemicals
Input: Sugars from cellulose, identical to the input in Phase 1. *Process*: Utilising DES as the catalytic medium, the sugars undergo transformations. *Outputs*: Formation of platform chemicals like hydroxymethylfurfural (HMF), which is fundamental in the synthesis of a multitude of high-value chemicals and biofuels.

Phase 4: Closing the loop
The post-catalysis spent DES, instead of being discarded as waste, is directed back into the fermentative production of PHA. This looping back exemplifies a sustainable approach, ensuring minimal wastage and maximum resource efficiency.

10.3.6 Challenges and future prospects

White biotechnology presents a promise for a sustainable future, intertwining biology's know-how with industrial processes to proffer eco-friendly solutions. However, while its potential is vast, the pathway to its extensive adoption is riddled with challenges. Scaling up biotechnological processes from the lab to industrial production is more intricate than merely expanding equipment size. The inherent complexity of biological systems means that they, unlike traditional chemical processes, rely on living organisms whose behaviour can fluctuate based on various factors, leading to inconsistent product yields and quality. Furthermore, aerobic operations necessitate efficient oxygen transfer, a task that becomes progressively challenging as the size of the reactor grows, with the central aim being to distribute oxygen uniformly without inflicting damage on cells due to excessive shear forces. Additionally, the exothermic nature of biological processes means that as they scale up, the effective dissipation of generated heat to maintain ideal temperatures becomes crucial. Moreover, ensuring the reproducibility of results, whether across different batches or during continuous operations, is vital for commercial success, but this too presents challenges given the variable nature of biological systems. Navigating the confluence of biology and industry presents an intriguing yet complex terrain, with economic considerations playing a main role in its widespread integration. Biotechnological ventures, particularly pioneering ones, demand hefty initial investments encompassing research and development, acquisition of specialised machinery, and onboarding of skilled staff. While biomass frequently emerges as an economical raw material choice, logistical hurdles associated with its aggregation, preservation, and preliminary processing can escalate costs. In the marketplace, products birthed from white biotechnology struggle against counterparts stemming from traditional methodologies. Ensuring cost-competitiveness, even when supplemented by ecological advantages, remains a formidable challenge. Furthermore, the trajectory of bioproduct production and market introduction, especially those leveraging genetically modified organisms, can be significantly influenced – either obstructed or expedited – by prevailing local regulations and policy frameworks.

Amid the rise of challenges, solutions also flourish, with the dynamic domain of white biotechnology continuously evolving, driven by both needs and innovative strides. Advances in synthetic biology now empower researchers to devise and assemble novel biological components, mechanisms and systems, presenting avenues to refine organisms for industrial applications in ways that transcend the bounds of classical genetic engineering. Moreover, grappling with the multifaceted nature of biological systems has instigated a paradigm shift towards a more encompassing systems biology perspective. Here, the emphasis is on decoding entire systems rather than isolated elements, a venture greatly facilitated by computational modelling. Concurrently, there is an ascending momentum behind the valorisation of industrial and agricultural residues, turning these potential waste streams into prized commodities. Such activities not only offer cost-effective feedstock alternatives but also present resolutions to waste management problems. Building on our earlier case study, the development of integrated biorefineries – producing multiple outputs from a single input – highlights the principles of maximum resource utilisation, increased process efficiency and economic viability. Moving away from broad-based solutions, the industry is now trending towards tailored approaches, specifically designed based on regional resource availability, market demands and regulatory frameworks.

10.4 Summary

This chapter has discussed selected achievements of global green and white biotechnology, which have had an unprecedented impact on the bioeconomy. It should be recognised that, without the biotechnological processes developed from the period of ancient biotechnology, through the era of classical biotechnology, and, above all into the times of its most intensive development, that is the age of modern biotechnology, the bioeconomy would not be able to be a global development strategy. The bioeconomy is currently rapidly and positively evolving towards respecting the needs and ecological limitations of the planet and drawing on the achievements of all areas of the biotechnology rainbow taking account of socio-economic and political changes, is thus becoming a new economic paradigm. It should be added that a new, exceptional perspective has now opened up for the development of biotechnology and the bioeconomy. This development has entered the phase of exponential growth, based on artificial intelligence (AI).[46] AI already plays a significant role in activities of such importance as machine learning, Big Data analytics, knowledge discovery and data mining, biomedical ontologies, knowledge-based reasoning, natural language processing, decision support and reasoning under uncertainty, temporal and spatial representation and inference, and methodological aspects of explainable AI. Specialists point to the fact that, in the not-so-distant future, the role of humans will only be to plan development so that it is beneficial for people and our planet.

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11 From biowaste to fertiliser

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11.1 The concept of the natural recycling of waste as nutrients

Technologies focused on natural use, mainly for fertiliser purposes and improving the properties of agricultural soils, have an important place among the numerous areas of waste processing.[1] A lot of waste contains valuable nutrients that can be part of renewable cycles.[2,3] Recycling of waste is one of the fundamental ways of implementing the principles of the circular economy (CE).[4]

The CE is a course of action which aims to transform the current unfavourable linear economy model into a circular model. The linear economy model is based on the principle of "take, produce, consume and discard", and it mistakenly assumes an infinity of natural resources and unlimited waste storage options.[5]

The CE strategy is to keep the obtained resources in circulation for as long as possible and to minimise waste generation through actions taken at every stage of the product life cycle. According to CE principles, waste becomes a raw material/product that remains in circulation for as long as possible. This makes it possible to reduce the exploitation of natural resources and reduce the production of waste that can be reused for the production of new products.[6,7]

The fertiliser economy is an important area of agriculture, the aim of which is to ensure global food security.[8] It is worth mentioning that, in the first agricultural systems, nutrients circulated in a closed loop (Figure 11.1). Emerging waste such as crop residues, animal excrements and domestic refuse was used as a source of nutrients for cultivated plants.[9,10] Progressive urbanisation, the dynamic development of the fertiliser industry in the 20th century, and also the emergence of specialised plant and animal farms, have contributed to increasing the amount of minerals and organic substances in circulation in agrosystems, and thus to disrupting their circulation (Figure 11.1). As a result, waste produced in increasing quantities has become not only a significant civilisational problem, but also a major source of pollution of water with biogenic substances, odour emissions and soil degradation.[11,12]

Identification of waste whose properties allow its use as fertiliser may directly reduce the consumption of mineral fertilisers. In consequence, this will bring significant environmental benefits, including a reduction in the

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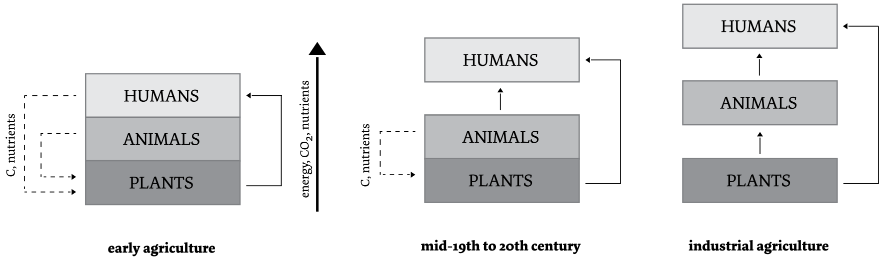

Figure 11.1 Circulation of fertiliser and carbon components in various periods of development (developed based on Magdoff et al.[13]).

extraction of fossil raw materials. It is worth mentioning that for years the fertiliser industry has been based on technologies which are centred on the processing of fossil resources. Fertiliser production requires high energy inputs, consumes non-renewable raw materials, and disrupts biogeochemical nitrogen and phosphorus cycles, which adversely affects the environment.[14] Moreover, in an era of rising prices of natural gas, as well as fertiliser and CO_2 emission allowances, waste valorisation is a real opportunity for the fertiliser industry.[15]

A large amount of waste generated in agri-food processing, on animal farms, in the municipal economy, and in many industries that use mineral resources, has significant potential as fertiliser.[16,17] Composting, thermal methods, and anaerobic fermentation are the most commonly used waste treatment technologies.[18,19,20,21] They ensure the sterilisation and stability of treated waste, and reduce nitrogen emissions. Waste incineration enables conversion into a useful fertiliser product – biomass combustion ash is a source of potassium, phosphorus and magnesium, all off which can be useful in agriculture.[22,23] The alkalising properties of ash allow it to be used on acid soils.[24] High-protein plant and animal residues (leguminous plants, feathers, skin) can be subjected to acid or alkaline hydrolysis, thus obtaining amino acids that stimulate plants, thereby increasing the availability and absorption of nutrients (amino acid chelates).[25,26] Organic-mineral fertilisers can be obtained by combining various kinds of waste, e.g. alkaline ash from the combustion of biomass and municipal sewage sludge, or sewage sludge with cellulose production waste.[27] Sewage sludge from municipal and industrial sewage treatment plants has great potential as fertiliser and is a source of nutrients.[28] Waste mineral wool from horticulture can be used to produce soil improvers, and waste from various industries can be used to produce calcium fertilisers needed for soil deacidification.[29,30]

The environmental use of waste for fertiliser purposes has multifaceted benefits. The use of waste for fertiliser production can significantly improve the balance of nutrients and organic matter in soils, and the need to manage the mass of produced waste enables the recycling of the substances contained within it.[31,32] Moreover, the environmental use of waste has a positive effect on the physical, chemical and biological properties of soils, and has a beneficial effect on the yield and chemical composition of crops. As a result, fertilisation of soil with fertilisers made from waste can contribute not only to getting rid of problematic waste, but also to significantly improving the properties of crops, e.g. an increase in the pH value of acid soils, an increase in the content of organic matter or clay fractions in soil, and an increase in plant-available forms of macro- and microelements.

The technology of processing waste for fertiliser purposes that is to be chosen must meet environmental protection requirements and ensure the production of safe food and feed. The optimal condition for the use of waste mixtures as fertiliser is their appropriate composition so as to minimise the risk of introducing heavy metals and other organic pollutants entering the soil environment.[33] In addition, for waste to be used in raw or processed form for fertilisation, it must meet legal requirements at the national and European level.

11.2 Possibilities of processing waste into fertilisers

The potential of the bioeconomy focuses on traditional sectors of the economy, such as agriculture, forestry and processing of agricultural and forestry products. Significant amounts of mineral and organic waste, a potential source of nutrients, are generated in the above sectors of the economy. Therefore, all waste generated should be environmentally managed in the form of mineral, organic or mineral-organic fertilisers, soil improvers, or in the form of growth and development stimulants for crops, mediums for crops and other products that increase the potential of the bioeconomy.[34,35]

The waste bioeconomy includes technologies that allow waste to be processed into useful products, including fertilisers. Some examples of trends of its use are provided below: (1) technologies of processing organic waste from agriculture (e.g. mushroom waste) and from sewage treatment plants (e.g. municipal sewage sludge) for composts, organic fertilisers, organic-mineral fertilisers, soil improvers; (2) technologies for processing organic waste from agriculture (e.g. slurry, plant biomass) and food management into energy products by methane fermentation with the possibility of obtaining fertiliser in the form of digestate; (3) technologies for nutrient recovery (e.g. N, P) from municipal sewage and liquid organic waste, e.g. the production of struvite (magnesium ammonium phosphate) for fertiliser purposes; (4) technologies for the recovery of useful water from sewage, slurry, and its reuse in the economy, agriculture; (5) use of waste mineral wool from horticulture for the production of soil improvers; (6) use of waste from various industries for the production of calcium fertilisers for the needs of soil deacidification in agriculture, e.g. the management of waste from the treatment of water intended for consumption and industrial purposes; (7) use of ashes from biomass combustion for the production of improvers, deacidifying agents; (8) technologies for managing waste from the fishing industry (e.g. waste fish, mussels, crabs), the poultry industry (e.g. chicken and goose eggshells), and from food management (e.g. spent coffee grounds) into mineral fertilisers (phosphor calcium magnesium) and organic-mineral fertilisers (Figure 11.2).[36,37]

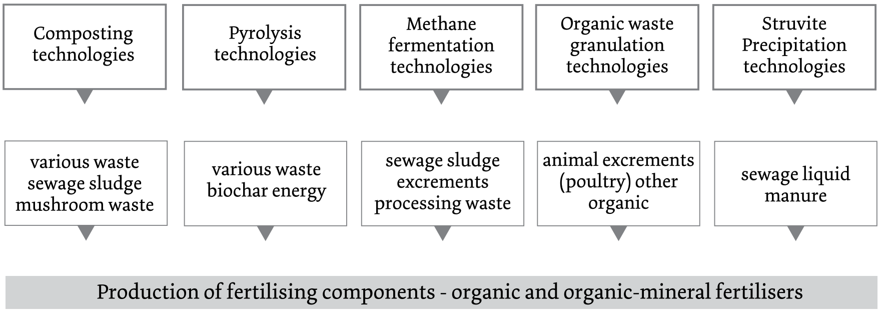

Figure 11.2 Directions of technologies or organic waste processing to fertilisers (based on Łabętowicz & Stępień[38]).

The above-mentioned technologies show that there are great possibilities for managing mineral and organic waste for fertilisers or fertiliser agents, supporting primary production in agriculture and forestry, and increasing the potential of the bioeconomy. As part of the bioeconomy, the generated waste should be processed in a way that the fertiliser components and organic matter contained therein return to cultivated fields, while maintaining environmental safety standards.[39]

Currently, highly specialised farms or enterprises, such as mushroom-growing cellars, large greenhouse complexes, poultry farms and biogas plants, are being built in rural areas. All of these facilities generate large amounts of organic waste suitable for use as fertiliser, after proper treatment (e.g. disinfection, stabilisation, grinding, drying and granulation). In suburban areas, municipal and industrial sewage treatment plants, energy plants (e.g. municipal boiler rooms, conventional power plants), sorting plants, composting plants and waste incineration plants, as well as municipal and industrial waste landfills, are being built and/or expanded – all these organisations also generate large amounts of waste that require specialised technology for its processing and treatment.[40,41]

For example, municipal sewage sludge and other organic waste cannot be deposited in landfills due to the large amount of organic matter and biogens (N, P), which should be environmentally managed. As part of the bioeconomy, there are the following possibilities for using sewage sludge: for the formation of reclamation layers in landfills, the production of composts and soil improvers, the production of substrates used in floriculture and horticulture, the production of energy and fibre plants, as well as for establishing gardens, parks and lawns, and for the production of biochar used e.g. for improving drought-affected lands, for the production of building materials and earthen structures, and, as a last resort, incineration with the possibility of managing ash as mineral fertiliser. A new product obtained in the form of biochar from sewage sludge, as well as from mushroom waste or manure at low temperatures (<350 °C), is characterised by the higher content and availability of nutrients, which may improve nutrition, growth and development of plants, especially under conditions of water scarcity and drought stress.[42,43]

In the case of mineral waste, for example, bottom ash from the incineration of agricultural and forestry biomass, and other inorganic waste, it is recommended (as part of the bioeconomy) that it should be used for: reclamation as part of nutrient recycling, creating reclamation layers in landfills and post-industrial areas, creating geopolymers based on ashes for solidifying heavy metals in the ground, improving soil frost resistance, increasing compression strength, soil compaction, creation of geopolymers from bottom ash and coconut fibres for soil stabilisation, production of soil improvers, addition to composts for their hygienisation and enrichment in nutrients, and the production of mineral and organic-mineral fertilisers. In addition to environmental management of bottom ash, it can be used for the levelling of post-mining sites, for the production of concrete, for the production of building materials (bricks), for the hardening of road surfaces and as a material for the levelling of areas for construction investments.[44,45]

The above use of organic and mineral waste requires a simple and advanced technology for its processing. Technologies related to the processing of this waste are diverse and depend on the type, chemical composition and specificity of the waste. Popular waste treatment technologies include: aging, composting, aerobic and anaerobic fermentation, pyrolysis of sewage sludge, carbonation, solar and thermal drying, vitrification of sewage sludge, stabilisation of sewage sludge with lime, liming materials produced on the basis of waste (disinfection), solidification, use for the preparation of building materials, and incineration – energy recovery, nutrient recovery from ashes, precious metal recovery from waste in dissolution and incineration processes.[46,47]

The technologies used are highly imperfect and sometimes involve high environmental risk; hence the need to improve the technology and increase its efficiency, so as to obtain new products, particularly fertilisers, which meet quality and environmental safety standards. Waste treatment technologies should make it possible to obtain, for example, fertiliser granules characterised by high durability, limited nuisance of odour emissions, easy transport and safe storage for a long period of time, so that the new product can be marketed.[48,49]

To sum up, the bioeconomy offers a very wide range of waste management possibilities, especially with regard to obtaining innovative mineral and organic-mineral fertilisers, and soil improvers, and the proposed technologies fit into the circular economy model.

11.3 Strategy and legal aspects of waste-based fertilisers at national and EU level

Waste can be used in agriculture as a source of nutrients, reducing the demand for mineral and natural fertilisers. From a logistical point of view, each plant, in addition to the main products, generates waste, which, at the national level

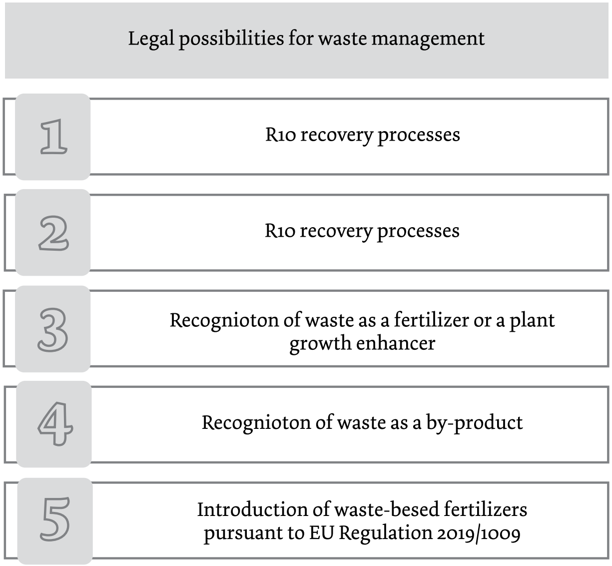

Figure 11.3 Legal possibilities for waste management (Source: Antonkiewicz et al.[51]).

in Poland, in accordance with the Regulation of the Minister of the Environment on the catalogue of wastes, receives its appropriate code.[50]

In the European Union, each member state can place fertilisers produced from waste directly on the market under EU Regulation 2019/1009. The condition for introducing new fertilisers from waste is to maintain appropriate criteria allowing these fertilisers to be used in agriculture and the environment.

Depending on the code, waste can be managed in different ways, and, from a legal point of view, the following solutions have been adopted (Figure 11.3):

1 R10 recovery processes

R10 recovery is land treatment that brings benefits to agriculture or in terms of improvement of the environment. Recovery conditions and types of waste allowed for such recovery are set out in the Regulation of the Minister of the Environment on the R10 recovery process[52] and directive on sewage sludge.[53] Waste should be used in such a manner and in such an amount that its use does not cause deterioration of the quality of soil or surface and groundwater, even with prolonged use. Therefore, when using waste, the important consideration is the content of heavy metals in the surface layer of soil (0–25 cm). In addition, the requirements regarding the detailed way of using fertilisers, which are set out in the Act on Fertilisers and Fertilisation, must be met.[54] The method of application is also important. The waste is to be applied evenly on the surface of the field to a depth of 30 cm and must be covered with soil or mixed with it. Waste must also meet the conditions governing the permissible content of pollutants in fertilisers and plant growth enhancers.[55,56,57] Pursuant to these regulations, waste must not contain more than 100 mg of chromium, 5 mg of cadmium, 60 mg of nickel, 140 mg of lead, and 2 mg of mercury per 1 kg of dry matter. Moreover, the presence of live eggs of the intestinal parasites *Ascaris* sp., *Trichuris* sp., and *Toxocara* sp., and bacteria of the *Salmonella* genus, is not allowed.

2 R3 recovery processes

The second possible recovery method is the R3 process – recycling or recovery of organic substances which are not used as solvents (including composting and other biological processes of transformation). R3 recovery conditions are defined in the Regulation of the Minister of the Environment on waste recovery outside installations and devices.[58] In addition to the obligation to meet the conditions described in the regulations, regulation of R10 and R3 recovery also requires appropriate documentation to be kept for inspection.[59,60]

3 Recognition of waste as a fertiliser or a plant growth enhancer

The issue of recognising waste as a fertiliser or a plant growth enhancer is governed by the Polish Act on Fertilisers and Fertilisation[61] and the Regulations of the Minister of Agriculture and Rural Development.[62] To obtain permission to place waste on the market as a fertiliser or a plant growth enhancer (i.e. soil improver, growth regulator, growing medium), the following documents must be submitted to the MARD:

1. reports on fertiliser tests carried out by authorised or accredited bodies. (Note: physical, physico-chemical, chemical, biological or agricultural tests are carried out on a sample of product taken by an authorised sampler, e.g. from a District Chemical-Agricultural Station);
2. opinion on compliance with quality requirements and opinion on suitability for use, issued depending on the purpose of the agent by various institutes;
3. draft instructions for the use and storage of the fertiliser or the plant growth enhancer.

Tests and opinion on meeting quality standards

To carry out the tests, the following need to be provided:

- a sample of the fertiliser taken by the sampler from a chemical-agricultural station or other accredited body in this field, and, in the case of fertiliser produced abroad – an authorised sampler in the producer's country. A collection protocol must be attached to the sample.

  The weight of a solid fertiliser sample is about 2 kg, while that of a liquid fertiliser sample is about 5 kg.

- filled-out manufacturer's/importer's declaration,
- description of the production technology with a list of raw materials used for the production of raw materials.

During the tests, all fertiliser parameters declared by the manufacturer or importer are analysed.

Opinion on the applicability of the fertiliser or the plant growth enhancer To prepare the opinion, the following are necessary:

- opinion on meeting quality requirements,
- results of agricultural tests of the fertiliser or growth stimulant,
- draft instructions for the use and storage.

Recognition of waste as a by-product. The issue of recognising waste as a by-product is regulated by the Polish Waste Act.[63] Pursuant to Article 10 of said act, "*an object or substance resulting from a production process that was not originally intended for its production, may be considered a by-product other than waste if all of the following criteria are fulfilled, inter alia: the substance or object meets all important requirements, including legal requirements, in terms of the product, environmental protection, and human life and health, for a pre-defined use, and such use will not lead to some generally negative environmental impact or impact on human life or health.*" The decision regarding the recognition of waste as a by-product is issued by a voivodship marshal.

Introduction of waste-based fertilisers pursuant to EU Regulation 2019/1009
Pursuant to this regulation, any producer of waste-based fertilisers may introduce them onto the market provided that a quality system is implemented in the production process to ensure repeatability of the composition and environmental safety. The EU Regulation (2019/1009) was established, among other things, so that some recycled waste, such as struvite, biochar, certain biowaste and ash-based products, etc., can be used for fertiliser production.

Fertilisers made from such waste may be introduced onto the market based on the manufacturer's declaration. In order for a fertiliser to be produced from waste, this waste must meet legal requirements regarding the content of harmful substances, as well as requirements for processes and techniques for its processing. It should be ensured that the use of these fertiliser products does not lead to general adverse effects for the environment or human health.

EU fertiliser products are made available on the European market only if they comply with this regulation, and they must meet the requirements of the annexes to this regulation:

- meet the requirements set out in Annex I for the relevant product function category;
- meet the requirements set out in Annex II for the relevant category or categories of stored material;

- be labelled in accordance with the labelling requirements specified in Annex III;
- carry out the procedure for assessing the conformity of the fertiliser product specified in Annex IV;
- the EU declaration of conformity is drawn up according to the model set out in Annex V.

By drawing up an EU declaration of conformity, the manufacturer assumes responsibility for the compliance of an EU fertiliser product with the requirements set out in the Regulation. As regards all matters not covered by Annexes I or II, EU fertiliser products must not pose a risk to human, animal or plant health, to safety or to the environment.

11.4 Environmental impact and economic potential of waste conversion to fertiliser

The environmental impact of converting waste into fertiliser depends on various factors, including the type of waste, the conversion process used, and the handling of the resulting fertiliser. Some potential environmental impacts are described in general terms below.

Reduced landfill usage
Landfill sites are associated with various biological, chemical, and physical reactions that pose potential environmental hazards. This is largely attributed to the generation of leachate and landfill gas.[64] Converting waste to fertiliser can divert organic material from landfills, reducing methane emissions (greenhouse gas) and the need for additional landfill space. In addition, there is growing pressure in the EU to limit the landfilling of waste in favour of other ways of use (recycling, composting). In accordance with the EU Landfill Directive, Member States are obligated to decrease the proportion of municipal waste destined for landfill to 10% or less of the total generated by 2035.[65,66]

Primary organic matter and nutrient enrichment
Due to the continuous decrease in the number of farm animals (livestock units) in the Czech Republic, the production of organic fertilisers (farmyard manure, slurry) is also decreasing,[67] and therefore alternative solutions are being sought (straw, green manure), including the use of biowaste for fertilisation. Fertilisers created from biowaste have a diverse composition. They do, however, contain primary organic matter, which is irreplaceable for soil fertility. The application of organic amendments and fertilisers has been shown to enhance both crop yields and soil organic matter.[68,69] Soil organic matter is the primary source of food and energy for soil microorganisms and their quality is determined by its lability. In the soil, this primary organic matter (carbon) undergoes two completely different but very important processes: predominant mineralisation, which results in plant-available nutrients, and minor humification associated with the formation of humic substances – humic acids, fulvic acids and humins.

The function of humus for the soil and its fertility is essential – sorption and exchange of ions, buffering, support of the soil structure (soil aggregates), retention of water in the soil, etc.[70,71]

Reduced consumption of mineral fertilisers

Overusing mineral fertilisers can lead to a range of environmental problems, including soil acidification, eutrophication, contributions to global warming, and loss of biodiversity.[72] Using organic waste-derived fertilisers may reduce the need for mineral fertilisers. Their consumption differs significantly between EU states, while in the Czech Republic it has decreased by more than half over the past 30 years to the current 105 kg of pure nutrients/ha/year (sum of 89 kg N + 11 kg P_2O_5 + 5 kg K_2O) with a predominant consumption of N and a below-average consumption of P and K.[73] Fertilisers obtained from biowaste contain both macroelements (N, P, K, Ca, Mg, S) and microelements (B, Mn, Cu, Zn, Fe, Mo)[74] and can thus improve the balance of nutrients in the soil and their mutual ratios. Due to the dependence of the production of (especially) nitrogenous mineral fertilisers on fossil fuels (natural gas), their price has increased significantly in recent years. A number of farmers have reduced the purchase of expensive (nitrogenous) mineral fertilisers and looked for alternatives in the form of liquid organic fertilisers (slurry, digestate, fugate) or fertilisers from biowaste, or have expanded the cultivation of legumes, capable of fixing atmospheric nitrogen.

Part of the consumption of mineral fertilisers has been replaced by other alternatives, which has its own economic and environmental impacts

However, there is also the question of the financial complexity of preparing fertilisers from biowaste, i.e. the chosen technological procedures (e.g. composting) and the subsequent final price of the fertiliser to make it interesting and attractive for farmers. In addition, the ambitious Green Deal[75] (Farm to Fork strategy, 2020) strategy envisages a reduction in nutrient losses from the soil by 2030 by a minimum of 50% and a reduction in the use of mineral fertilisers by 20%, and an increase in the area of land farmed under organic farming to 25% (www.europarl.europa.eu). From this perspective, the future importance of organic fertilisers (classical and alternative, including those from biowaste) for soil fertility, required yields and their quality is obvious.

Reducing the risk of water eutrophication

A surplus of nutrients in waters (especially N and P) can lead to eutrophication of waters. The sources of these nutrients can be diverse (e.g. wastewater or excrements from households), including agriculture (mineral and organic fertilisers). Phosphorus from fertilisers is subject to intensive soil sorption and the risk of its leaching into waters is low. Ammonium nitrogen ($N\text{-}NH_4^+$) is similarly sorbed in the soil. The problem may be in nitrate nitrogen ($N\text{-}NO_3^-$), which is very mobile and can be more easily leached out of the soil and contribute to the eutrophication of waters.[76] A greater risk for water eutrophication is high doses of N mineral fertilisers than a reasonable application of organic fertilisers including fertilisers from biowaste.

Risk elements in fertilisers under control

All fertilisers considered to be 'put into circulation' (legislative term, i.e. sold, donated, etc.) must meet the limits on selected risk elements (mg/kg fertiliser dry matter) – Cd, Pb, Hg, As, Cr, Cu, Mo, Ni and Zn. If even one element exceeds the limit, the fertiliser must not be used. The second measure is the dose of organic fertilisers per ha, which can be regulated by legislation. In the Czech Republic, it is, for example, a maximum of 20 tons of dry matter of fertiliser per ha in 3 years for fertilisers with a dry matter of more than 13% (compost, separate, etc.). To put it briefly – fertilisers are safe for the soil.

Transportation, distribution, carbon footprint

The transportation of waste to conversion facilities and distribution of the resulting fertiliser may have associated environmental impacts. The energy demand for transport will be an issue in particular. It would be ideal to produce these fertilisers from waste at a local level with a short transport distance and a low carbon footprint.

Chemical and biological residues

Depending on the waste source, there could be potential residues of contaminants or pollutants that need to be managed properly. The occurrence of organic contaminants in bio-based fertilisers can result in unwanted chemical residues within the treated soil.[77,78] These contaminants can subsequently be absorbed by the crops or leach into the groundwater, posing potential risks to both human health and the environment. However, the research conducted by Das et al.[79] showed that soil samples from a field treated with bio-based fertilisers from diverse sources (agricultural, poultry, veterinary, and sludge) revealed minimal traces of contaminants. The findings indicate that the contaminants detected in the soil treated with bio-based fertilisers may have origins distinct from the fertilisers themselves. Indeed, certain guidelines must be followed for bio-based fertilisers. For instance, during composting, organic material goes through a specific thermophilic stage, allowing for the sanitation of waste by eliminating pathogenic microorganisms.[80]

11.5 Case study – mixtures of sewage sludge and cellulose waste as a soil improver

Chemical composition of sewage sludge is mainly determined by the type of sewage (municipal, industrial) and the technology and level of its treatment. The determined physical, chemical and biological properties of the sewage sludge have a substantial effect on the trend in their use.[81] Due to the presence of many harmful substances in sewage sludge (especially in industrial sludge), its environmental use seems to be limited.[82] Nevertheless, attempts are being made to refine this waste with other substances to improve its properties. Cellulose production waste in the form of sludge is another waste that is a potential fertiliser material. In general, sewage sludge from paper mills, due to its harmfulness to the environment, is subjected, inter alia, to incineration processes.[83] Taking into account the high content of organic substances and minerals in sewage sludge, it is substantiated to use this waste for agrotechnical purposes, as well as for the production of soil improvers, substrates used in horticulture.[84,85]

Sludge from paper production, as well as municipal sewage sludge, contains many valuable nutrients, including macroelements and microelements, which can be environmentally recovered.[86] Recovery of nutrients from the above-mentioned waste can be carried out using crops, energy and reclamation plants, under which this waste will be used. The condition for using this waste is its proper processing, mixing it in an appropriate proportion so that it meets the requirements for soil improvers and does not deteriorate soil properties.

The case study presents the possibilities of using these two types of waste, differing in physical and chemical composition, in the form of a fertiliser mixture, as a soil improver.

Origin and characteristics of sewage sludge

The analysed cellulose production waste is generated at the "Beskidy" paper and cardboard factory in Wadowice, Poland. The factory runs a production business focused primarily on the recycling of paper waste. In the production processes, old newspapers, composite packaging and worn clothing are used. The final product of the production process is paper towel and building board. The by-product is sewage sludge in the form of cellulose production waste. Due to the high content of macroelements and microelements, the above-mentioned waste can be utilised as substrate for decorative plants.[87]

The municipal sewage sludge that was used in the case study was obtained from a mechanical-biological sewage treatment plant in Słomniki. The sewage sludge was stabilised (aerobic stabilisation) and hygienised with burnt lime. The content of heavy metals in the sewage sludge did not exceed the permissible amounts specified in the Regulation of the Minister of the Environment on municipal sewage sludge. Moreover, there were no microbiological contaminants in the sewage sludge.[88]

Composition of the mixture and conditions of the experiment (case studies)

The optimal condition for environmental use of cellulose production waste and sewage sludge is to compose them properly in order to minimise the risk caused by introduction of heavy metals to the soil environment.

To do so, in the field experiment, a mixture of the above-mentioned types of waste (mixed in a weight ratio of 1:1) was used, which, once introduced to soil, supplied nutrients for the tested plants and improved the physico-chemical properties of the soil (Table 11.1). In the case study, to compare the effect of the waste mixture, a control treatment (without waste), as well as treatments with only cellulose production waste and sewage sludge, were used (Table 11.1).

The one-factor field experiment was set up in a randomised block design, in four replications. The plot area was 6 m^2. The distance between the plots was

Table 11.1 Treatments and doses of waste applied in the field experiment

Treatmentno.	*Treatments*	*Waste dose [Mg DM · ha^1]*	
		Cellulose production waste (CPW)	*Sewage sludge (SS)*
1	Control (C)	—	—
2	Cellulose production waste (CPW)	50	—
3	Sewage sludge (SS)	—	50
4	Mixture I: CPW x SS	25	25
5	Mixture II: CPW x SS	50	50

0.5 m. The experimental design comprised five treatments differing in the dose of the introduced types of waste and their mixtures (Table 9.1). The applied waste doses (50 and 100 Mg·ha^{-1} DM) were supposed to be suitable for substrates used in reclamation and revitalisation of post-industrial areas.[89] The method of obtaining the mixture of cellulose production waste and municipal sewage sludge was registered at the Patent Office of the Republic of Poland (Patent Number PL411157-A1).

The mixture sown in the field experiment consisted of seeds of grasses and papilionaceous plants. The amount of the mixture sown was 30 kg·ha^{-1}. The rate of seeding of the mixture was increased due to possible adverse climatic-soil conditions. Mineral fertilisation (NPK) was not used in the field experiment, which was explained by saying that the used waste would be a source of nutrients for the sown plant mixture.

Results obtained

The use of only cellulose production waste at a dose of 50 Mg·ha^{-1} reduced the yield of the plant mixture. In contrast, composed mixtures of cellulose production waste with sewage sludge and application to soil in a single (25 Mg·ha^{-1}) and double dose (50 Mg·ha^{-1}) increased the plant mixture yield significantly. The increase in the plant mixture yield was more than 25% compared to the control (Figure 11.4).

The study showed that the waste mixture used also increased macronutrients in the plant mixture. The plant mixture had an optimal chemical composition, with the possibility of feed use. The alkaline cellulose production sludge used in the waste mixture also affected the immobilisation of heavy metals in the soil, thus preventing the biomass from taking these elements up from the plant mixture.

The study showed that cellulose-containing waste participates in the biosorption, which includes chemisorption, complexing, as well as adsorption on the surface and pores, ion exchange, microprecipitation, heavy hydroxide condensation on biolayers and surface adsorption.[90] The above-mentioned biosorption processes can also occur in soil solutions, limiting the processes of metal uptake by the tested plants.

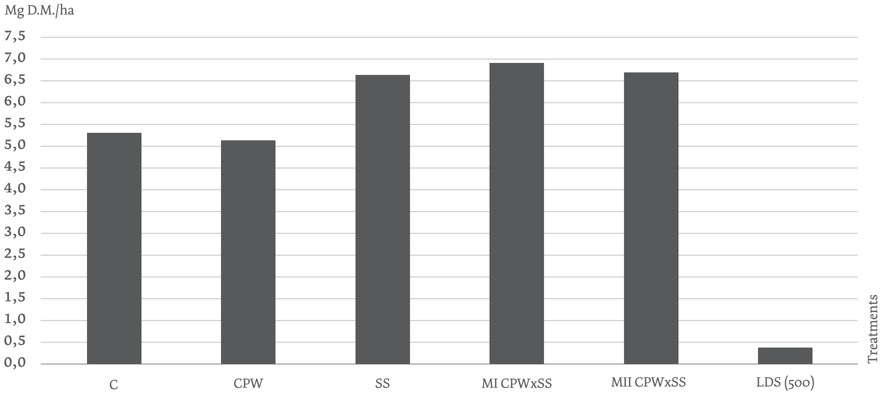

Figure 11.4 Yield of plants mixture (Mg D.M.·ha^{-1}). Treatments – see Table 11.1.

Biomass of the plant mixture obtained in the field experiment meets requirements in terms of the content of Cr, Ni, Cd, Pb, Cu and Zn set for good-quality feeds.[91] The applied cellulose production waste and municipal sewage sludge, as well as their mixtures, did not result in the content of the above-mentioned metals in the plant biomass intended for feed purposes being exceeded. The low content of heavy metals in the plant biomass results from low solubility of these metals from cellulose production waste.[92,93] Other studies confirm that alkaline waste (containing calcium compounds) contains heavy metals in forms hardly available to plants.[94,95]

The obtained biomass ought to be intended for compost for reclamation, or for energy purposes, or for other non-feed-related purposes.[96] The cellulose production waste and municipal sewage sludge used and their mixtures can be used as a horticultural substrate, as a fertiliser for growing energy crops and plants intended for ornamental, economic, non-consumer and non-feed purposes.[97,98]

In conclusion, these types of waste are beneficial to the soil environment and plant biomass, do not pose a threat in terms of content and availability of heavy metals, but each batch intended for environmental management should undergo chemical and microbiological tests.

11.6 Case study – Biomass ash with sewage sludge as a soil improver

One of the technologies for managing biomass ash and municipal sewage sludge is their use to produce a soil improver. Ash from biomass combustion has a high content in nutrients necessary for plants. By contrast, apart from nutrients, municipal sewage sludge contains substantial amounts of organic matter that improves the physico-chemical properties of soil.[99,100]

However, bottom ash also has adverse physico-chemical properties, such as: alkalinity, salinity, dustiness and excessive content of heavy metals. That is why it is common practice to improve it with an additive or by mixing with municipal sewage sludge. The obtained ash-sludge mixtures constitute a potential source of plant-available macroelements and have a beneficial effect on the substrate.[101,102]

The case study hypothesised that the prepared waste mixtures, containing biomass ash and bituminous coal ash, as well as municipal sewage sludge, can improve the physico-chemical properties of soil, which in turn should stimulate the growth and development of plants, and thereby influence the amount of yield and the chemical composition of plants.

Study materials and methods

The study on the possibility of using waste mixtures to improve plant growth and development, as well as the physico-chemical properties of soil was conducted under field experiment conditions.

The field experiment covered not only the types of waste that were applied separately, but also their mixtures. The first mixture ('MC') was prepared from ash obtained from combustion of bituminous coal and municipal sewage sludge. The second mixture ('MB') was prepared from ash obtained from combustion of biomass and municipal sewage sludge. The above-mentioned mixtures were prepared (mixed) in a 1:1 weight ratio in terms of dry matter.

The field experiment was set up in a randomised block design, in four replications. The plot area was 6 m^2. The scheme of the experiment comprised eight treatments: one control and seven treatments with ash from bituminous coal and biomass, municipal sewage sludge, as well as their mixtures applied in two doses (Table 11.2).

The mixture sown in the field experiment consisted of grasses and legumes. Mineral fertilisation (NPK) was not used in the field experiment, since the assumption was that the waste used (bottom ash and municipal sewage sludge) would be a source of nutrients for the sown plant mixture.

Results obtained

Physico-chemical properties of the soil and waste

The bottom ash was loose, whereas the municipal sewage sludge was 'earthy'. The earthy form of the sewage sludge is desirable owing to the ease of

Table 11.2 Treatments and doses of waste applied in the field experiment

*Treatments**	*Waste dose [Mg DM·ha^{-1}]*		
	AC	*AB*	*MSS*
Ct	-	-	-
AC	50		-
AB	-	50	-
MSS	-	-	50
MC I	25	-	25
MB I	-	25	25
MC II	50	-	50
MB II	-	50	50

* Ct—Control; AC—Ash from combustion of bituminous coal; AB—Ash from combustion of biomass; MSS—Municipal sewage sludge MC—Mixture of coal ash and sewage sludge; MB—Mixture of ash from biomass and sewage sludge; I—Single dose of the mixtures, II—Double dose of the mixtures.

application to soil and formation of soil aggregates, particularly on degraded lands (including on waste landfills and on lands being reclaimed).

The bottom ash varied in terms of pH($H_2$0) values, which ranged from 10.2 to 12.3. Ash from combustion of bituminous coal was more alkaline compared to biomass ash. A high pH value of the applied bottom ash is of considerable importance in deacidification of the soil environment. The reaction of the municipal sewage sludge was neutral.

Organic carbon content in the cultivated soil to which the waste was applied was over 10.2 $g \cdot kg^{-1}$ DM and was 3.4-fold higher compared to bottom ash from combustion of bituminous coal. Of the applied types of waste, the highest amount of organic carbon was recorded in municipal sewage sludge. The organic carbon content in the sewage sludge was: 12; 37; and 115-fold higher compared to the content in the soil, biomass ash and coal ash, respectively. Such considerable variation in organic carbon content in the waste can be also explained by the technology of its production.

<u>The content of macroelements (N, P, K, Na, Mg, Ca) in the soil and waste</u>

The applied types of waste were highly diversified in terms of the content of biogenic substances. It was established that the municipal sewage sludge contained the greatest amount of total nitrogen. The content of this element was over 821-fold higher compared to the content in biomass ash, and over 83-fold higher compared to the content in ash from bituminous coal. Nitrogen content in the sewage sludge was over 13-fold higher compared to the content in the soil. The applied municipal sewage sludge, compared to bottom ash and the cultivated soil, also contained the greatest amount of calcium. The high calcium content in the sewage sludge can be explained by hygienisation of this waste with calcium oxide. Of the applied types of waste, the largest quantities of P, K and Mg were found in biomass ash. The municipal sewage sludge used in the experiment contained significantly more macroelements compared to the amounts present in the soil. The content of these elements in ash depends on the chemical composition of biomass, in other words on the type of plant raw material that is combusted.

<u>The size of the yield and chemical composition of the plant mixture</u>

The ash-sludge mixtures (MC and MB) applied in a single and double dose significantly increased the plant mixture yield compared to the control. The mixtures, composed of biomass ash and sewage sludge, applied in a single and double dose (treatments MB I, MB II), were more yield-forming than the mixtures based on bituminous coal (treatments MC I, MC II). This relationship stems from the greater availability of nutrients derived from biomass ash compared to hard coal ash (Figure 11.5).

The case study found that only the applied hard coal and biomass ash reduced the yield, which is due to an imbalance in the soil solution and high salinity. The ash-sludge mixtures used also increased the content in macronutrients such as K, Ca, Mg, Na in the plant mixture. The study shows that

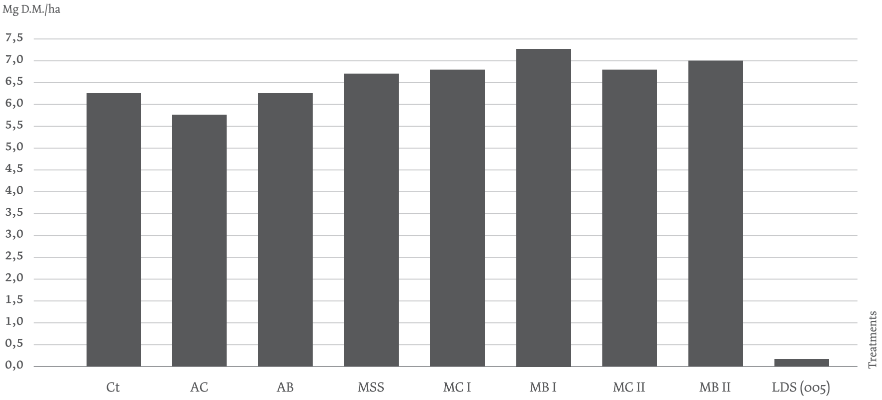

Figure 11.5 Yield of plants mixture (Mg D.M.·ha^{-1}). Treatments – see Table 11.2.

biomass ash was richer in macroelements (P, K, Mg and Ca) compared to coal ash and there were therefore more nutrients in the biomass of the plant mixture.

In conclusion, it was established that the applied ash-sludge mixtures improved the physico-chemical properties of the soil by increasing the availability of biogenic elements for plants. Of the applied ash-sludge mixtures, it is recommended to use mixtures of ash from biomass and sewage sludge in agriculture and reclamation. This is due to the favourable physico-chemical properties of these mixtures.

11.7 Case study – Digestate as a fertiliser and a soil improver

Manures from stables, crop residues, wastes from the food industry, municipal wastes, and dedicated energy crops are the main feedstocks for anaerobic digestion (AD) in biogas plants. The residual product of AD, called digestate (=biogas effluents = biogas residues, or biogas slurry, when animal manures are digested), is usually used as a fertiliser.[103] Biogas and digestate are the end-products of anaerobic digestion of organic raw material which is an important source of renewable energy.

Recently, there has been a considerable increase in the number of biogas stations in the Czech Republic. Estimated annual digestate production is of the order of 7.9 million tonnes and deployment of biogas stations in the regions is irregular. For this reason, practical problems frequently arise as to how to utilise the digestate effectively and/or where to apply it (in compliance with Czech legislation – for example: the Czech Directive on Nitrates and Restrictions in the Vulnerable Areas). Considering the fact that digestate is produced throughout the whole year, possibilities are being sought of using it to fertilise not only arable crops but also vegetables. Whereas information on using digestate to fertilise arable crops is relatively abundant, in the case of vegetables, the reverse is true.[104]

Field and pot trials conducted to date report positive effects of digestate application to arable land in terms of yields,[105,106] or no significant effects.[107,108] Literature on the application of digestates as fertilisers for vegetables is very scarce. Expert opinion on the properties and possibilities for practical use of digestate as an organic fertiliser is divided.[109,110] Digestion is associated with large losses of organic carbon (C).[111] Möller & Müller[112] reported that as much as 95% of the feedstock organic matter is degraded, depending on the feedstock composition. However, the digestate produced is rich in nitrogen (N) and has a high NH_4^+-N/total N ratio, making it potentially suitable as a fertiliser. Digestates contain a high amount of nitrogen and potassium,[113] while the phosphorus (P) content, among other macronutrients, is significantly lower. Besides macronutrients, digestates contain micronutrients too. The application of digestates can therefore allow considerable savings to be made on costs for the purchase of mineral fertilisers.[114] The risk elements in the digestates are also under control, as already discussed above in section 11.4. The maximum dose of digestates in the Czech Republic is 10 tons of dry matter of fertiliser per ha in 3 years. It is necessary to incorporate digestate into the soil before sowing and planting, which will reduce nutrient losses (ammonia volatilisation) and potential odours, and will increase nutrient use efficiency. Application in rows on the soil surface during the vegetation period is also possible for selected crops (e.g. maize), including a system of split doses. A single dose of digestate should not exceed 25 $Mg \cdot ha^{-1}$ FM (Fresh Matter).[115]

The chemical composition of digestates fluctuates. However, we can give a concrete example from our own pot experiment with kohlrabi plants:[116] the dry matter content of the digestate was 6.99%, pH 8.16 and C:N ratio 4.8:1 (nitrogen readily available, because the C:N ratio is below 10). Table 11.3 gives the analysis of the digestate for the total content of nutrients and Table 11.4 shows the treatments applied in the experiments.

There were significant differences between years in all parameters. The weight of single kohlrabi bulbs in the unfertilised control was significantly lower in both years (33.1–46.9%) than in the digestate treatment (100%).

Table 11.3 Total nutrient content (%) of the digestate used to study the response of kohlrabi[117]

	N	*P*	*K*	*Ca*	*Mg*
Fresh matter	0.537	0.087	0.483	0.108	0.051

Table 11.4 Treatments applied in the experiments[118]

Treatment	*Description*	*Rate of nutrients (g/pot): N-P-K-Mg*	*Fertiliser used*
1	Control	0	—
2	Digestate	1.5–0.24–1.35–0.14	Digestate
3	Digestate + P	1.5–0.48–1.35–0.14	Digestate, TSP

TSP – triple superphosphate (19.6% P).

Table 11.5 The effect of fertilisers on kohlrabi bulb weights in both years[119]

Treatment	*Description*	*2014*		*2015*	
		G	*rel. %*	*g*	*rel. %*
1	Control	42^{aA}	33.1	69^{aB}	46.9
2	Digestate	127^{bA}	100.0	147^{bB}	100.0
3	Digestate + P	141^{cA}	111.0	168^{cB}	114.3

Mean values of kohlrabi bulb weights (n = 4). Different small letters indicate significant differences at the level of $\alpha = 0.05$ among individual treatments within the same year and different uppercase letters (A, B) indicate significant differences of $\alpha = 0.05$ among individual years

Table 11.6 The effect of fertilisers on the content of nitrate (NO_3^-) in kohlrabi in both years[121]

Treatment	*Description*	*2014*		*2015*	
		mg·kg⁻¹ FM	*rel. %*	*mg·kg⁻¹ FM*	*rel. %*
1	Control	135^{aA}	41.2	163^{aB}	32.0
2	Digestate	327^{bA}	100.0	509^{bB}	100.0
3	Digestate+P	315^{bA}	96.3	486^{bB}	95.5

Mean values of kohlrabi bulb nitrates (n = 4). Different small letters indicate significant differences of $\alpha = 0.05$ among individual treatments within the same year and different uppercase letters (A, B) indicate significant differences of $\alpha = 0.05$ among individual years; FM – fresh matter

Digestate supplemented with P (treatment 3) increased the bulb yield significantly by 11.0–14.3% compared with pure digestate (treatment 2) (Table 11.5).

In both years the content of bulb nitrates (mg $NO_3^- \cdot kg^{-1}$ FM (fresh matter)) was significantly the lowest in the unfertilised control (135 and 163, respectively), (Table 11.6). After applications of digestate, the nitrate content (mg $NO_3^- \cdot kg^{-1}$ FM) increased significantly in both years, i.e. to 315–327 (2014) and to 486–509 (2015) compared to unfertilised control. In two years, the content of ascorbic acid ($mg \cdot kg^{-1}$ FM) did not differ among the three treatments (274–288 in 2014 and 311–329 in 2015). Digestates can be recommended for kohlrabi fertilisation prior to planting.[120]

In conclusion, digestates are organic fertilisers with readily available nitrogen (C:N below 10), but their effects and action are more similar to combined mineral fertilisers, since they contain hardly any labile sources of primary organic matter (source of energy for soil microorganisms), but mainly contain (semi-)stable forms of more complex cellulose structures and especially lignin itself. Therefore, it is necessary to add quality sources of primary labile organic matter such as manure, straw (post-harvest residues), composts and green manure to fields which are regularly fertilised with digestates. Also, in order to support the soil structure and avoid the formation of soil crusts, it is necessary to balance the ratio of bivalent (Ca^{2+}, Mg^{2+}) and monovalent (K^+, Na^+) cations in the soil by regular liming.

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