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Closed-circle bioeconomy: Applied aspects of agricultural implementation

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Abstract: In the face of global challenges, innovative methods of production and consumption are vital, and the bioeconomy signifies a transformational shift based on biological processes, minimal energy use and full integration of resources into ecosystems. This study focused on a sectoral analysis of bioeconomy opportunities with a focus on bioenergy and waste management in an agriculture sustainable approach. Literature-based analysis was used to approach the research objectives of the roadmap design methods. A comprehensive sectoral analysis of the bioeconomy was conducted with a special emphasis on bioenergy and food security. A conditional roadmap of bioeconomy implementation clusters was presented, which is in line with global trends. Agriculture, being an integral part of the bioeconomy, faces challenges due to ecosystem degradation, water scarcity, and poverty. The global trend of biotechnology adoption in agriculture offers benefits for sustainable bio-economic development, including soil conservation, cost reduction, job creation and improved food quality. Thus, the bioeconomy has significant potential to address global challenges and achieve sustainable development, which requires innovation, regional adaptation and a commitment to harmonise economic growth with environmental conservation. Further research into the involvement of the rural areas in the development of bioeconomy is required.

Keywords: sustainability; bioresources; biomass; recycling; innovation

Bioeconomy encompasses a diverse range of sectors, including agriculture, forestry, fisheries, bioenergy, and bioproducts, all of which rely on biological resources for sustainable production and innovation (European Commission 2022; Siebert et al. 2022). Within this framework, agricultural biomass and waste represent a particularly important area, providing opportunities for value addition, renewable energy generation, and the development of bio-based products. By focusing on the agricultural approach, this study highlights how sector-specific strategies can contribute to the broader objectives of the bioeconomy.

The current challenges of climate change, land and ecosystem degradation, combined with the growing demand for food and energy, are forcing humanity to look for new ways of production and consumption. A sustainable and circular bioeconomy contributes significantly to addressing these challenges (Rojas-Serrano et al. 2024). The bioeconomy represents a new frontier in economic development that prioritises the reuse and recycling of secondary raw materials, including waste. This approach fosters an environment conducive to the repeated and cyclical utilisation of resources, resulting in increased gross domestic product and advancements in a country's socio-economic development (Hodgson et al. 2022).

The bioeconomy is also seen as one of the aspects of economic activity, an economy based on production

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paradigms that are associated with biological processes, use natural resources from the environment, require minimal energy consumption, and do not pollute the environment, as the input resources are used more than once and are completely transformed in the ecosystem (Tan and Lamers 2021; Holden et al. 2023). In summary, the bioeconomy in terms of production encompasses elements: the sustainable use of renewable biomass and efficient bioprocessing, the incorporation of enabling technologies like biotechnology, and its widespread application across sectors such as agriculture, forestry, healthcare, and industry according to the FAO (2018).

Bioprocessing of organic waste is gaining increasing importance worldwide for the production of valuable bio-based products such as biofertilisers, bioethanol, biohydrogen, biogas, bioplastics, organic acids and bioenzymes (Adetunji et al. 2023; Velasquez-Pinas et al. 2023). For example, this strategy enables wastewater reuse, reduces water sources pollution and produces valuable compounds that contribute to human health, such as phycobiliproteins, carotenoids, omega-3 fatty acids, exopolysaccharides, mycosporine-like amino acids, and serve as a source of bioenergy (Najar-Almanzor et al. 2023). Valenti et al. (2023) provided a rationale for using agroindustrial by-products as energy sources and initiating efficient bioeconomic processes for sustainable utilisation of renewable natural resources. Different areas of biomass processing are emphasised within the circular bioeconomy system, such as lignin-derived biochar to improve the conversion of the typical lignin monomer, which is a challenging substrate to digest, as outlined by Valenti et al. (2023). However, a comprehensive environmental study must be performed before the introduction of biorefineries. For this purpose, environmental life cycle assessment is widely applied (Kiehbadroudinezhad et al. 2023). Life cycle assessment, life cycle cost and social life cycle assessment should be completed to ensure market adoption of derived products and business models (Siegfried et al. 2023a).

The development of agriculture based on bioeconomy principles is essential for achieving sustainable development and food security despite climate change and limited natural resources. Implementing circular approaches in the agricultural sector can reduce greenhouse gas emissions, improve soil fertility, and enhance the efficiency of biomass use (Khanna et al. 2024). Bioeconomy practices require innovative biotechnologies such as precision farming and genetic modification, which optimise agricultural processes and reduce resource consumption (Cidón et al. 2021). The European Investment Bank (2018) emphasises the role of the bioeconomy in utilising renewable resources from both land and sea to produce food, materials and energy, thus enhancing resource efficiency and supporting the transition to a low-carbon economy. Organic farming, as an essential component of the bioeconomy, supports ecosystem protection through efficient water and land management while minimising chemical inputs (Cidón et al. 2021). For the successful adoption of bioeconomic practices, not only technological innovations are necessary, but also state support programs and market mechanisms that encourage farmers to implement new approaches (Khanna et al. 2024).

Building on the results of previous research, this study provides a sectoral analysis of bioeconomy opportunities, illustrated with examples from the literature, with particular attention to bioenergy and waste management within a sustainable agricultural framework.

MATERIAL AND METHODS

A literature-based analysis was conducted using comprehensive searches of the Scopus and Web of Science (WoS) databases, complemented by online research support tools to explore scholarly literature on bioeconomy. The scope of the study primarily covers the European Union countries, while selected examples from other global regions are included to provide comparative context. This focus ensures the relevance of the findings to EU-specific policies and sectoral developments, particularly in agriculture and bioenergy.

To identify emerging research trends, a set of carefully selected keywords was applied, reflecting the agricultural focus of the study: 'bioeconomy AND biogas', 'bioeconomics AND rural areas', 'renewable resources AND bioeconomy', and 'agriculture AND waste AND bioeconomics'. While the broader bioeconomy can include forestry, bio-based construction materials, and other sectors, this study concentrates on agricultural biomass, waste valorisation, and bioenergy applications to maintain a coherent scope.

The analysis tools with an initial example of the results obtained are presented:

i) An examination of trends in publication activity over time, supported by illustrative examples from the literature, makes it possible to trace the evolving dynamics of global interest in the bioeconomy field, with particular attention to historical milestones in sustainable economic development.

ii) Analysing the applications and directions of bioeconomy research, as reflected in selected publications, helps to clarify sector-specific developments within this emerging economic paradigm.

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iii) A review of publication dynamics across different countries highlights, through documented examples, the principal contributors to the advancement of bioproducts for economic development in various global regions.

iv) Considering the sources of project financing, as identified in relevant publications, allows for an assessment of the funding landscape within the field of bioeconomy.

Visual illustrating the development of bioeconomy, with a focus on the bioenergy sector, were created using Canva software to provide a clear and accessible representation of research trends and sectoral interconnections.

RESULTS AND DISCUSSION

Overview of sectoral implementation of 'bioeconomy' and its main components. Bioeconomy represents alternative solutions that could harness innovation, promote economic growth and, most importantly, produce beneficial outcomes for society and the environment. The national programmes of different countries have significant potential for the development of the bioeconomy, selected examples of which are presented in Table 1.

Within the European Union, several member states stand out as leaders in the development and implementation of national bioeconomy strategies (D'Adamo et al. 2020; Siebert et al. 2022). Germany has established a comprehensive National Bioeconomy Strategy, strongly linking research, innovation, and industrial deployment. Finland's updated Bioeconomy Strategy 2022–2035 emphasises value creation, climate neutrality, and cross-sectoral collaboration. The Netherlands has consistently advanced bio-based policies since the mid-2000s, focusing on biomass valorisation and regional implementation. Sweden has adopted roadmaps for sustainable use of biological resources, while France launched a national Bioeconomy Strategy and Action Plan (2018–2020), with substantial investments in biotechnology and agricultural biogas. Comparative research confirms that these countries are among the frontrunners in shaping the European bioeconomy through coordinated policies, innovation support, and regional engagement (Siegfried et al. 2023a, b; Petropoulos et al. 2025).

The circular economy aims to change the classical linear model of production by focusing on products and services that minimise waste and other types of pollution.

The above scenarios were used as indicators of the impact categories of the life cycle assessment, which are presented in Table 2.

The environmental impact of biogas plants throughout their full life cycle can be further improved by good agricultural practices for digestate application, as well as by reducing the amount of fossil fuels used in the cultivation and transportation of energy crops (Fuchsz and Kohlheb 2015).

The factors influencing the development of the agricultural system in the context of bioeconomy advancement have been classified in Figure 1.

Social factors such as urbanisation and demographic changes play a crucial role in agricultural development. The increasing trend of urbanisation and the migration of rural populations to urban areas put pressure on rural territories, necessitating increased labour productivity to compensate for the workforce shortage. Migration also occurs within the agricultural sector itself, with people moving from less favourable areas to more favourable ones (Jha and Bag 2019) According to Saketta (2022), improving rural-urban linkages, such as enhancing infrastructure and integrating rural

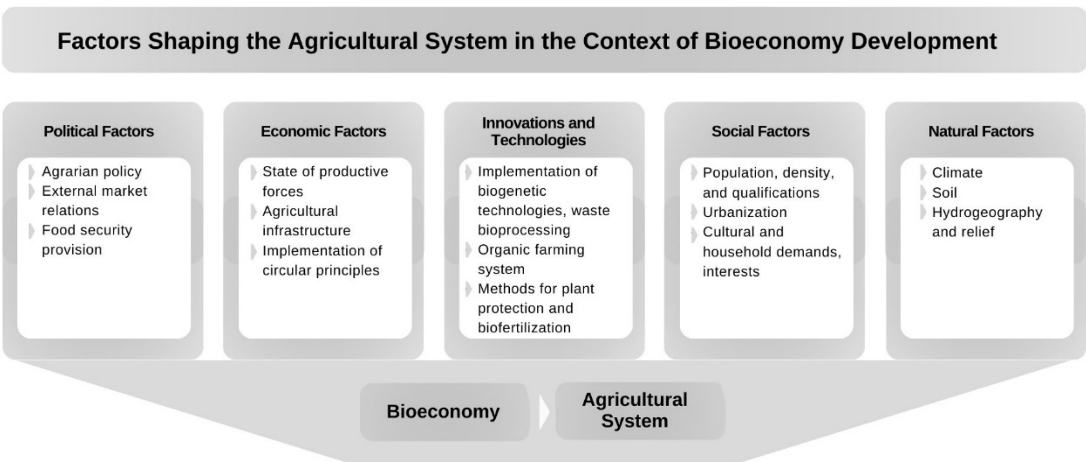

Figure 1. Factors shaping the agricultural system within the context of bioeconomy developmen

Source: Authors' own elaboration

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Table 1. National programs for the development of bioeconomy

Programme name, country, or region	Brief overview	Source
Nordic initiative on bioeconomy, Nordic countries	The Nordic platform, grounded in national programs, strengthens Nordic and international research and innovation efforts for the shift toward a holistic bioeconomy. It offers new perspectives on how collaborative research and innovation can advance biological and sustainable development within society.	NordForsk (n.d.), Lyche Solheim et al. (2023)
Bioeconomic strategy of the EU	The EU Bioeconomy Strategy promotes the sustainable use of biological resources for food, energy, and bio-based products while reducing dependence on non-renewable materials and supporting climate goals. Its action plan focuses on boosting bio-based sectors and investments, fostering regional deployment, and ensuring ecological sustainability through monitoring and ecosystem protection.	Liobikiene and Miceikienė (2023) Krömer et al. (2024) European Commission, (2022) Ryś-Jurek (2024)
National bioeconomy strategy, the Netherlands	The National Bioeconomy Strategy in the Netherlands aims to transition from fossil fuels to a sustainable, bio-based economy, leveraging the country's strengths in agriculture and industry. This strategy is driven by the need to address climate change and resource dependency while capitalising on economic opportunities. The Dutch government adopts a facilitative governance approach, promoting regional clusters and innovation, which contrasts with more traditional top-down strategies seen in other countries.	Interreg North-West Europe (2018) Samen and Kaldiyarov (2025) Robaey et al. (2022)
National bioeconomy strategy, Sweden	The National Bioeconomy Strategy in Sweden aims to transition towards a sustainable economy by leveraging its natural resources, particularly in the forestry sector. This strategy is characterised by a focus on biorefineries, innovation, and collaboration among various stakeholders. The following sections outline key aspects of Sweden's bioeconomy strategy.	Fossil Free Sweden (n.d.) Petropoulos et al. (2025)
National bioeconomy strategy, France	The National Bioeconomy Strategy in France aims to transition towards a sustainable economy by leveraging biological resources. This strategy encompasses various sectors, including agriculture, biomedicine, and environmental management, with a focus on reducing reliance on fossil fuels and enhancing resource efficiency. Key components of the strategy include the promotion of biotechnologies, the development of innovative biotherapies, and the optimisation of residual biomass utilisation.	Rao and Pliquet (2023) Javourez et al. (2023)
National bioeconomy strategy, Finland	The National Bioeconomy Strategy of Finland aims to transition towards a low-carbon and resource-efficient society, leveraging renewable natural resources and sustainable development. It emphasises the forestry sector, alongside agriculture and circular economy initiatives, to foster a comprehensive bioeconomic framework.	MEAE (2022) Toivanen (2021)

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Table 1 to be continued.

Programme name, country, or region	Brief overview	Source
National bioeconomy strategy, Italy	Italy's National Bioeconomy Strategy is part of a broader European effort to transition from a fossil-based economy to one that is bio-based, leveraging renewable resources. This strategy is aligned with the European Bioeconomy Strategy and aims to address grand societal challenges by promoting sustainable production and consumption practices. Italy's approach is characterised by a focus on policy mixes that integrate various sectors, including energy and manufacturing, to foster a bio-based economy. The strategy emphasises the importance of multi-level governance within the European Union to reinforce this transition.	Marchetti and Palahí (2020) Petropoulos et al. (2025)
National bioeconomy strategy, Germany	The program aims to develop innovative solutions aligned with the 2030 Agenda for Sustainable Development, recognising and leveraging the potential of the bioeconomy while staying within ecological limits. It emphasises the enhancement and application of biological knowledge, with a particular focus on biomass as a renewable raw material. The program seeks to position Germany as a global leader in bioeconomy innovation by fostering societal involvement and strengthening both national and international collaboration. Biogenic resources are viewed as more than mere substitutes for fossil materials; they enable the creation of new products, such as nutritional supplements for improved infant food, advanced composite materials for construction or automotive applications, and optimised, resilient crops.	BMBF (2020) Jafari et al. (2023) Siegfried et al. (2023b) Siebert et al. (2022)
The Bioeconomy, Bioenergy, Bioproduct (B3) Program, USA	The program seeks to create new opportunities for farmers and ranchers through the promotion of sustainable biomass crop cultivation, the development of regional supply chains, and the advancement of bioproducts, biomaterials, and advanced biofuels, while also testing commercialisation models. The program aims to reduce carbon emissions by supporting resilient agricultural and food systems and enhancing ecosystem services to promote ecological well-being. In addition, it focuses on increasing domestic job creation in rural and urban areas by cultivating a skilled workforce in emerging sectors and decreasing dependence on imported oil.	The National Institute of Food and Agriculture (n.d.)

Source: Authors' own elaboration

communities into agricultural value chains, is essential for maximising the benefits of urbanisation while minimising its negative impacts. In some regions, migration trend can lead to a significant reduction in the agricultural labour force, increasing labour costs and relying heavily on older, less efficient workers, which further affects agricultural productivity (Dokubo et al. 2023). Therefore, improving living and working conditions is essential not only between rural and urban areas but also among different rural regions. Where objective conditions make this difficult, the agricultural system and its intensity must adapt accordingly.

Natural conditions (climate, soil, terrain, hydrology) have always been fundamental factors shaping

https://doi.org/10.17221/36/2025-AGRICECON

Table 2. Life cycle assessment studies for organic waste management: Case study

Waste management scenarios	Impact categories	Characteristics	Source
(1) undifferentiated collection with subsequent biostabilisation of the organic fraction and its final disposal at the landfill (2) separate collection of the organic fraction with subsequent compost production	carcinogens/non-carcinogens amount of fine particles ionising radiation depletion of the ozone layer/global warming fine organic matter aquatic/terrestrial ecotoxicity terrestrial acids/nutrients land use/mineral extraction water acidification/eutrophication non-renewable energy	An analysis of the scenarios for the case of Italy shows that: (1) has the best performance in ten of the fifteen impact categories considered (2) has the lowest impact in the categories of carcinogens, land use, water eutrophication, global warming, and mineral extraction. Taking into account the actual performance of the biostabilisation process, (2) can be the most favourable scenario only if there is a significant reduction in air emissions (in particular, hydrogen sulphide, particulate matter, ammonia, and NMVOCs). At the level of endpoints, (2) has the best score in the category 'damage from climate change'.	Buratti et al. (2015)
(1) incinerators (2) combined biogas and composting (3) mechanical and biological treatment	depletion of the ozone layer/global warming acidification terrestrial eutrophication marine/freshwater eutrophication carcinogenicity depletion of abiotic resources – fossils/elements formation of a specific substance ecotoxicity/ionising radiation	For the case of the Danish-German region, scenario (1) showed the best environmental performance in 10 of the 14 impact categories assessed, but four impact categories have either values very close to zero impact (ionising radiation and depletion of the ozone layer) or too high uncertainty to draw conclusions (carcinogenicity and ecotoxicity). Scenario (3) had only environmental burdens, as the facility did not substitute any goods and used electricity and diesel, and had direct processing-related emissions such as nitrous oxide.	Jensen et al. (2016)
(1) anaerobic digestion followed by composting of the solid digestate (2) incineration (3) anaerobic digestion followed by incineration	global warming depletion of mineral resources/metals aquatic ecotoxicity freshwater/marine eutrophication toxicity to humans formation of specific substance photochemical oxidation terrestrial acidity terrestrial eutrophication	Anaerobic digestion followed by composting (1) is the most economically and environmentally sound option. - Incineration (2) showed comparable environmental impacts but increased the levelised cost of energy. System (3) did not reduce the environmental impact and the costs were higher than the other options.	Mayer et al. (2020)
(1) anaerobic digestion (2) incineration (3) hydrothermal carbonisation	depletion of the ozone layer/global warming depletion of mineral resources formation of a specific substance terrestrial acidity carcinogenicity freshwater/marine eutrophication	Scenario (1) is the preferred treatment pathway for organic fraction of municipal solid waste and food waste, if the eutrophication process is not disturbed. Implementing step (3) may be appropriate for the organic fraction of municipal solid waste and food waste under certain circumstances. Importantly, heat must be provided by a non-fossil resource, which can be achieved if anaerobic digestion is combined with a hydrothermal carbonisation process.	Mayer et al. (2021)

https://doi.org/10.17221/36/2025-AGRICECON

agriculture, as it depends on soil fertility, solar energy, water, and other natural resources. These factors are more stable and less dynamic than social or technological influences, and some remain beyond human control. While they largely determine the nature of agriculture, they do not change rapidly. However, under consistent natural conditions, agricultural systems can evolve significantly due to advances in science, technology, economics, and politics. For example, arid steppes are ideal for wheat cultivation, which continues to be in high demand, making these areas suitable for long-term crop production. In such regions, dry farming techniques are essential to conserve water. In erosion-prone areas, soil conservation practices must be prioritised, while in mountainous regions with challenging terrain, livestock and sheep farming are often more viable than commercial crop production (Tarraf Ibrahem 2024). Additionally, innovations, especially in biotechnology, energy, and industrial development, profoundly influence agricultural systems by enhancing production methods, transportation, and processing, contributing significantly to agricultural progress within the closed-circle bioeconomy framework (Munaweera et al. 2022; Wei et al. 2022).

Agroforestry systems (AFS), as noted in do Carmo Martinell et al. (2019), are one of the options for mitigating environmental impact while simultaneously improving the livelihoods of small-scale farmers in agricultural regions. A study conducted by do Carmo Martinell et al. (2019), in the Cerrado biome assessed the contribution of five biodiverse AFS to mitigating the effects of global warming and providing ecosystem services to small farmers in Brazil. The results demonstrate the significant carbon sequestration capacity of these systems, with negative GHG values ranging from –263 to –496 t $CO_2e \cdot ha^{-1}$. Additionally, households benefit from the microclimate regulation and aesthetic advantages offered by AFS. Future agroforestry projects in rural communities could play a crucial role in improving household living conditions and environmental conservation. However, efforts must be made to provide farmers with reliable knowledge, financial support, and access to markets to ensure their success.

Another study conducted by Zhou (2024) explored the interaction between digital finance and the incomes of farming households in the agricultural sector. It considered the application of digital financing tools in bio-agriculture, focusing on their mechanisms to expand market access, change financing modes, and increase outreach to agricultural households.

Waste management remains a challenge in agriculture; however, there are opportunities to add value through effective waste processing strategies. A study by Muhl and Oliveira (2022) provides an overview of agricultural waste processing technologies, identifying various biological and thermal solutions. Heavy metals, chemical, and biological pollutants present significant challenges in treatment processes. Among the technologies that have been extensively researched in the scientific community are anaerobic digestion and composting. Other approaches include microalgae cultivation, pyrolysis, algae biorefineries, incineration, combustion, gasification, anaerobic co-digestion, hydrothermal carbonisation, vermicomposting, biosynthesis processes, dry anaerobic digestion, and photobioreactors. The implementation of these technologies is a crucial step towards achieving a closed-circuit bioeconomy model.

Innovation aspect of bioeconomy implementation. The success of the circular bioeconomy hinges on a harmonious blend of cutting-edge technology, innovative approaches, and time-honoured knowledge. The main components of the bioeconomy are: development and utilisation of genomic, post-genomic, and complex cellular technologies to produce new products and processes; use of renewable biomass sources for sustainable production and environmental protection; integration of biotechnological knowledge and applications in various sectors of the economy (Siegfried et al. 2023a). This is also closely related to the possibilities of using different types of wastes in bioprocesses such as phosphogypsum (Chernysh et al. 2021). Nevertheless, at its core, it is firmly rooted in biodiversity. It is imperative to seamlessly integrate various forms of technological advancement into the pre-existing cycles within the bioeconomy. This imperative arises from the fact that biodiversity plays a pivotal role in shaping the adaptability and evolution of biological systems in response to a dynamic environment, thereby underpinning the long-term sustainability of our bioresources (Palahí 2020). Accordingly, we have formed a conditional roadmap by clusters of bioeconomy implementation (Figure 2), which reflects the trends in the global development of the bioeconomy (BP 2021; Andhalkar et al. 2023).

One example of the development of the bioeconomy in the world is bioenergy. As reported by the BP (2021), experts estimate that proven oil reserves last for 40–50 years, gas reserves for 80 years, and coal reserves for about 400 years. Furthermore, the trend of increasing gas prices over the past 10 years has increased rapidly,

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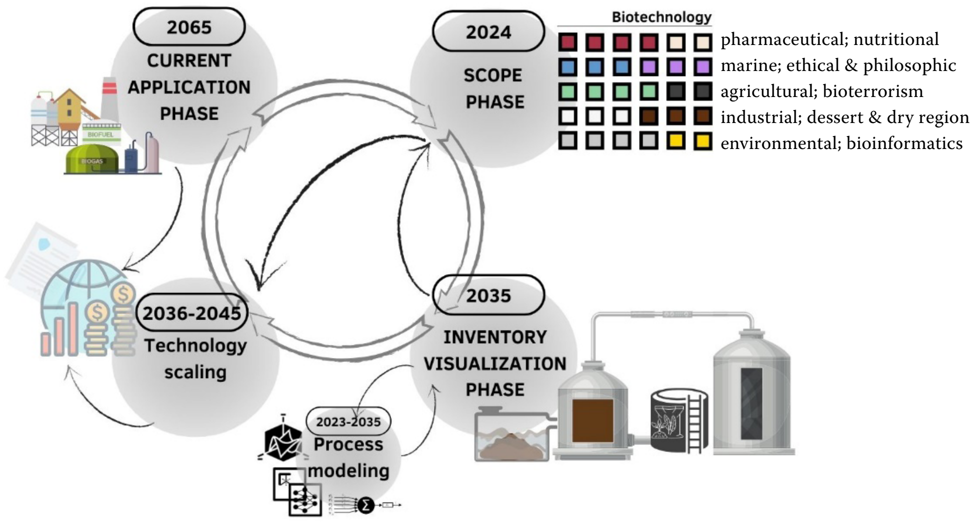

Figure 2. Model of circular economy based on biotechnology development with phases of the roadmap

Source: Authors' own elaboration

which is an economic prerequisite for the active development of bioenergy.

After analysing studies on life cycle assessment of organic waste management (Buratti et al. 2015; Jensen et al. 2016; Mayer et al. 2020, 2021), the following possible management scenarios were identified: undifferentiated collection; landfill disposal; mechanical and biological treatment; incineration in incinerators; combination of anaerobic digestion with incineration; anaerobic digestion accompanied by solid digestate; separate collection and production of high quality compost; combined biogas and composting production; hydrothermal carbonisation. Furthermore, a crucial aspect is the processing of various types of waste, including those from the chemical industry. Specifically, this includes the integration of phosphogypsum – a byproduct of phosphate fertiliser production – into agricultural bioprocesses (Chernysh et al. 2021). Figure 3 illustrates the involvement of agriculture and forestry in the bioenergy sector as a supplier of stable raw materials.

The primary commercial challenge in biofuel production is the high cost of production, which directly affects the fuel price. In addition to reducing the cost of biofuels, technological advances play a crucial role in reducing production costs, leading to biofuels becoming a prominent source of renewable energy. Therefore, the development of advanced biodiesel and

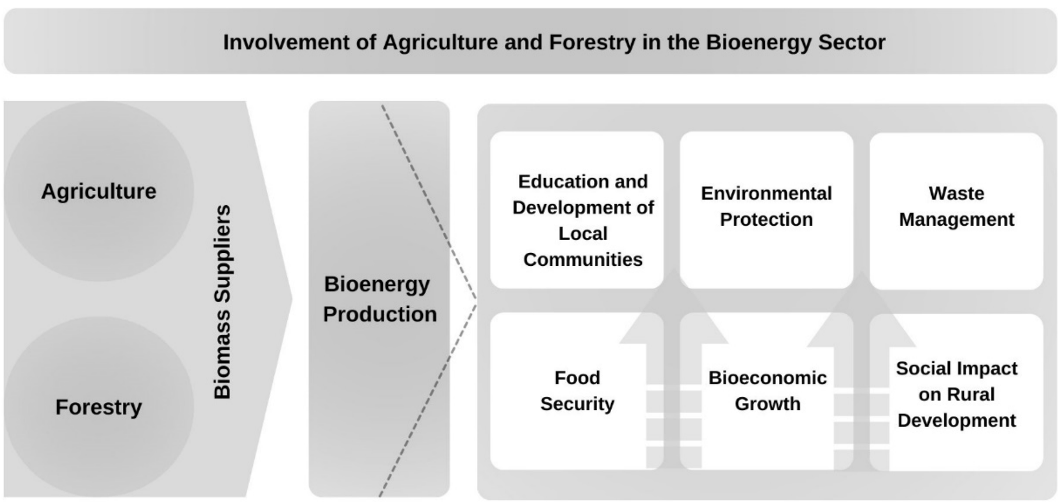

Figure 3. Involvement of agriculture and forestry in the bioenergy sector

Source: Authors' own elaboration

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bioethanol production technologies is imperative to increasing biofuel production output (Hasan et al. 2023).

In addition, fiscal and regulatory policies to attract investors and fund research on biofuels from biomass feedstocks remain a challenge. Given the substantial costs associated with project implementation and infrastructure development, it may be challenging for the private sector to fully finance such projects. Obtaining a loan or financial support to initiate investments in the biofuel industry can be a difficult task under certain circumstances.

The advancement of the bioenergy economy requires overcoming several challenges related to competition for agricultural land, rising food prices, difficulties with technological progress, and obstacles in infrastructure development (Hasan et al. 2023). The current state of biotechnology allows for the production of environmentally friendly products while preserving the environment, significantly contributing to the development of methods for efficient and sustainable business operations.

Another aspect of the bioeconomy that should be discussed is the impact on adaptation to climate change. The reliance on imported fossil resources in the face of current geopolitical challenges has led to significant increases in operational costs for many European companies and municipalities. Seruga et al. (2022) show that using the methanogenesis from municipal biowaste in order to generate electricity is associated with a 25.3–26.6% reduction in CO_2 emissions compared to a baseline scenario with conventional electricity generation. It is important to emphasise that biological waste, unlike energy crops, is considered a sustainable feedstock for biogas and one of the priority areas for bioeconomy development.

The agricultural sector in the development of the bioeconomy will continually require investments in the modernisation of physical assets, the expansion of the use of biotechnology in production processes, and the enhancement of resource efficiency to produce sustainable raw materials for green growth. Innovations are crucial for the future of the bioeconomy sector as a whole. The transition to a low-carbon and circular economy opens up potential new markets with increasing demand for biomass (for bioenergy) and biomaterials for products. Therefore, balanced and sustainable territorial development supports cohesion and requires investments in rural areas.

CONCLUSION

A review of the sectoral realisation of the bioeconomy and its main components was carried out, making it possible to find key directions for step-by-step implementation in the long-term planning of roadmaps for the development of bioeconomy in regions of the world. Bioenergy was identified as an important sector of bioeconomy implementation in the current realities of the development of energy security policy. The factors shaping the agricultural system in the context of bioeconomy development were analysed and grouped. A model of circular economy based on biotechnology development with roadmap stages was developed. The directions of participation of agriculture and forestry in the development of the bioenergy sector were supported. It can be expected that in the future, research in the field of bioeconomy will focus more on the participation of rural areas in the development of the bioeconomy.

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