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# Advancing circular bioeconomy: trends, clusters, and roadmaps in biofuel production and waste valorisation

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**Abstract.** Today, one of the important tasks of bioeconomy development is waste management based on the principles of environmental management and bioenergy production. In the context of this issue, this review focusses on the analysis of current trends in biofuel production that involve sustainable feedstocks and the valorisation of waste into useful bioproducts in agriculture. The scientometric method included the use of Scopus and Web of Science databases to compare the coverage of the research topic with keyword chain optimization. In addition, bioinformational databases was used to support the involvement of secondary raw materials in the bioprocessing cycle. The implementation of the research objectives resulted in the identification of bioeconomy clusters that emphasize the importance of developing specific regional circular bioeconomy strategies while avoiding 'one-size-fits-all' solutions for individual sectoral technologies. An example of bioeconomy development in the world is bioenergy. The structure of bioenergy has been analysed. A roadmap for biotechnology modernisation was proposed using the example of anaerobic waste conversion process as part of the implementation of a circular bioeconomy. The stages of the roadmap for the modernisation of bioenergy technologies were analysed within the framework of the sectoral implementation of the circular bioeconomy. The efficiency indicators for the implementation of bioeconomy in agricultural production have been determined. In addition, an important direction unifying anaerobic technologies with the agricultural sector is the enrichment of digestates with macro and microelements, which is possible due to mineral additives, for example, phosphogypsum. This direction was also considered from the point of view of environmental safety.

**Key words:** bioeconomy, renewable energy, agricultural production, waste recycling.

## INTRODUCTION

When discussing economic development with a focus on biotechnology, emphasis is placed on circular bioeconomy as a thermodynamic approach to the instability of the economic process based on the concept of entropy. McDougal (2022) presents a model of bioenergetic evolution at the planetary level that implies that, in theory, significant public investment in terrestrial solar generation may be required to realise a planetary energy transition and prevent ecological collapse. This demonstrates the importance of energy for economic evolution at the planetary level. Leff (2021) demonstrates a nongentropic productivity that the authors claim mobilises the ecological organisation of life on the planet based on an alternative production paradigm. This ecotechnological paradigm increases the biosphere's production of natural use values by converting solar energy into biomass generated by photosynthesis and symbiogenesis, with a technological system designed to increase this potential, utilising and limiting entropic decay, rooting sustainable livelihoods in the cultural imagination. Additionally, cross-sector collaboration and regional incentives for waste management need to be implemented. The high costs associated with retrofitting biogas facilities, collecting and preprocessing raw materials, as well as developing downstream production processes for customers, could potentially impede the rapid integration of the concept of biowaste supply chain and its products into the market (Siegfried et al., 2023). The development of bioeconomy based on sectoral integration of bioproducts of different target orientation is of strategic importance for the leading economies of the world (China, USA, Germany, Sweden, etc.). At the same time, bioenergy is increasingly being demanded as a branch of applied development and participation as a stable raw material base for various types of waste (Hu et al., 2023, Moustakas et al., 2023).

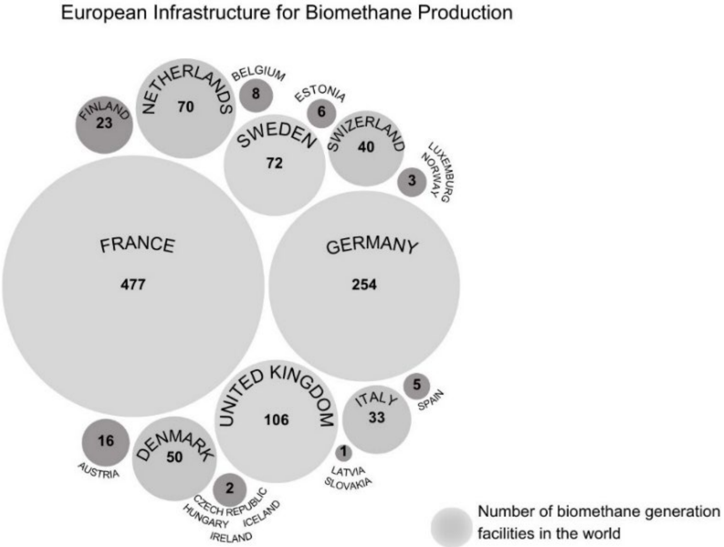

**Figure 1.** Biomethane production projects in the world (based on Statistical information sourced from IEA Bioenergy).

According to the data compiled, the diagram shown in Fig. 1 illustrates the countries that are leading in the implementation of biomethane technologies. France, with 477 projects, leads the chart, with biomethane used primarily by public authorities and companies, which currently represent the majority of biomethane consumers, primarily using it as a transportation fuel (European Biogas Association, 2017).

Germany, with 254 biomethane projects, is second, with biomethane primarily used for electricity production in combined heat and power (CHP) plants, and its use as fuel is indirectly supported and developing (European Biogas Association, 2020). The United Kingdom, which has 106 biomethane projects, involves most of these projects being connected to gas distribution networks (Green Gas Certification, 2024). Sweden, the Netherlands, Denmark, and Finland are among the countries with well-developed biomethane technologies, with biomethane projects in these countries accounting for about a quarter of their biogas plants. Governments around the world are supporting this trend, furthering the development of the biomethane sector.

Despite the fact that biomethane is currently not regulated at the European level, some countries, such as Germany, have introduced legislation that regulates the introduction of biomethane mesh. At the initial stage, when the first biomethane plants were built in Germany, there was no such legislation in the country. The first innovative plants were established by agreement between the main stakeholders, such as the biogas plant operator, the natural gas network operator, and the authorities (Thrän et al., 2023).

It should be emphasised that in Ukraine, only a small number of companies (up to 2% of the total) have the opportunity to implement biomethane (BM) projects with a capacity of 100 $m^3$ $h^{-1}$ of biogas or more, using only waste from their own production. To a greater extent, these are large-scale poultry farms, sugar, and distilleries. The possibility of implementing large-scale projects (2,000 $m^3$ $h^{-1}$ of biogas or more) using the raw materials of a single enterprise is limited to single examples. On the basis of this, promising BM production projects may be those that combine the fermentation of waste from several enterprises and/or plant material. A large-scale increase in biomethane production requires the use of part of agricultural land to grow plant material (Geletukha et al., 2022).

Biological waste is a source of environmental pollution and a significant repository of valuable resources because of the large amount of organic and biodegradable components it contains that can be reused. Recycling biological waste into resources through bioprocessing can help reduce carbon emissions and the growing environmental problems associated with solid waste (Mishra et al., 2023). Continuous innovation and research into large-scale fermentation processes are needed to make this technology more economically feasible and competitive, while providing global markets with an ever growing and more diverse range of high value biobased products (Verardi et al., 2023).

Therefore, this study focusses on reviewing trends in the development of biofuel potential as a branch of the bioeconomy with a focus on the recycling of wastes. The following objectives of the study were achieved:

- Bioeconomy strategy for the growth of industrial sectors
- Biowaste as a sustainable feedstock for energy production within the framework of bioeconomy promotion
- Evaluation of a mineral additive phosphogypsum for use in bioproduction.

## MATERIALS AND METHODS

Life cycle assessments are an important tool for comparing a new biorefinery concept with landfill disposal. Specifying the environmental impacts of anaerobic digestion plants on individual substrate types, the impacted stations are shown in Fig. 2.

Canva, as a user-friendly graphic design software that offers a wide array of features to create visually engaging content, allowed us to create informative maps, incorporating key data, and trends related to the bioenergy sector. The software was used to develop visually appealing maps that effectively communicate the data collected during the bibliometric analysis of relevant bioenergy data.

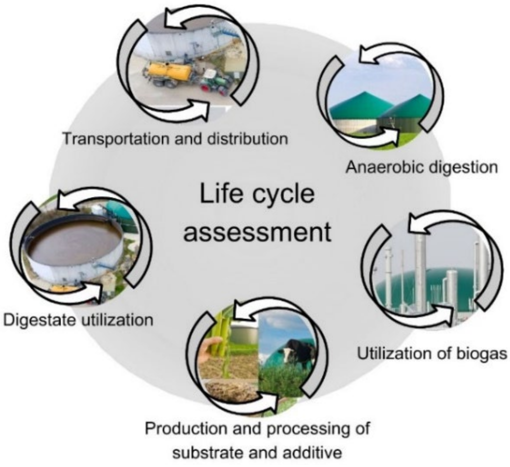

**Figure 2.** Life cycle assessment steps for organic waste utilisation through anaerobic digestion to biogas production (based on Ugwu et al., 2022).

### Analytical tools of scientometric databases in the analysis of trends in the development of bioenergy technologies of anaerobic fermentation

To optimise analytical research, the Scopus and WoS database platforms have a set of various online tools that can be used to analyse publication activity in the field of anaerobic fermentation for bioproducts.

To identify emerging research trends, various combinations of keywords were used, including energy bioeconomy; waste bioprocessing bioeconomy; biofuel waste bioeconomy; anaerobic digestion bioeconomy; biodiesel bioeconomy; biogas bioeconomy; Life Cycle Assessment Bioeconomy; Bioinformation databases.

Using the analytical tools of the Scopus and WoS databases, it is possible to work with charts based on bibliographic data according to categories:

- number of published works by years (Fig. 3a);
- distribution of publications by publications indexed by the database;
- number of thematic publications among authors and organizations;
- quantitative distribution of published documents by territorial principle (Fig. 3, b);
- comparison of institutions that provide funding for research (Fig. 3, c);
- distribution of documents by type and field of knowledge to which the text belongs.

The total number of publications in databases amounted to 2,456 papers. The field of bioenergy, as a major component of the development of the bioeconomy, began to actively gain momentum in publications starting from 2015. At that time, the importance of opportunities offered by a sustainable bioeconomy became important. Since 2019, there has been a threefold increase in the number of publications on this subject, peaking in 2022 with the registration of 514 scientific papers per year (Fig. 3, a). Research and development in this area are actively continuing to make progress.

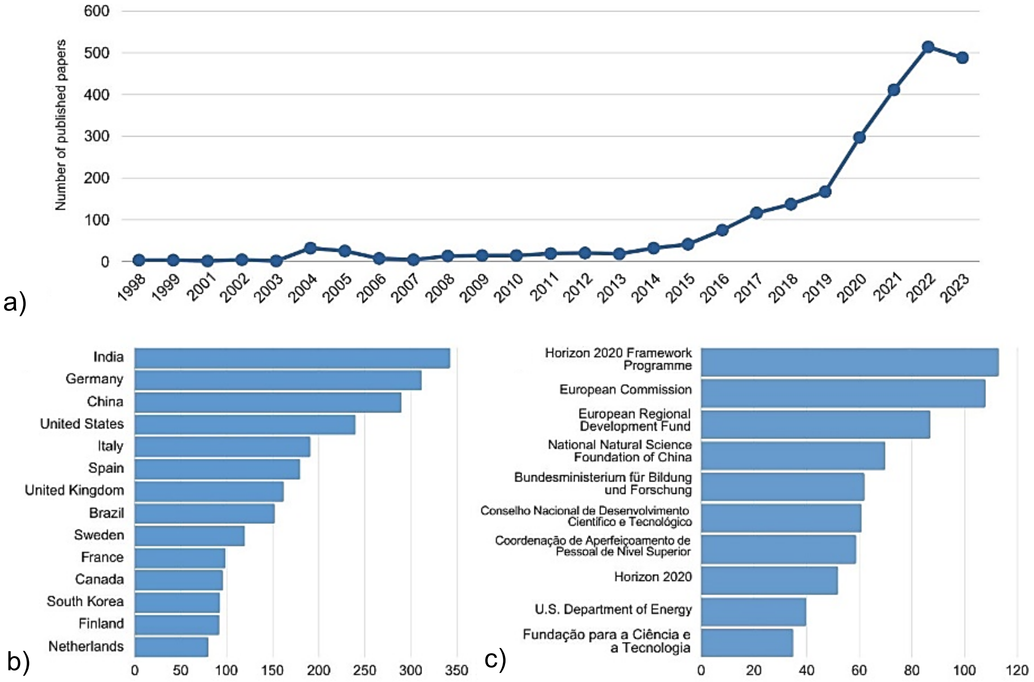

**Figure 3.** Bibliometric data processing: a) Number of articles published by year; b) Distribution of published papers by territorial scope; c) Comparison of institutions that provide research funding.

In terms of the geographical distribution of publication activity (Fig. 3, b), most of the research in this area is conducted by scientists from Indian, German scientific academies, demonstrating more than 300 published studies each. At the same time, China and the United States exhibit comparable levels of activity, each accounting for more than 200 publications. This indicates their significant contribution to the progress and development of the bioenergy sector.

However, most of the research funding comes from funds from the European Union (Fig. 3, c). In addition, leading positions are held by specialists from Italy, Spain, the UK, and other EU countries (Fig. 3, b).

It is worth noting that the types of documents are dominated by articles related to such fields of knowledge as environmental sciences and energy, as well as engineering, including chemical engineering, which means that most of the publications are aimed at improving the environmental situation by comprehensively solving several problems at once - utilisation of organic waste and obtaining alternative sources of fuel from biomass.

### Use of bioinformatic electronic databases: KEGG database, BacDive and EAWAG-BBD

Bioinformatics databases have a narrow specialisation for microbiologists. The main aspects that were taken into account when using them in this work include the ability to analyse the metabolic pathways of microorganisms associated with the utilisation of the mineral components of phosphogypsum.

One of the most known and extensive databases for gene networks, metabolic and signalling pathways is KEGG PATHWAY. A special option of the database interface allows you to customise the diagram for a specific type of organism, and the number of species depends on how universal the biological process is displayed in the diagram. The KEGG REST API allows you to perform and run queries on the information available in the KEGG database (Kanehisa et al., 2017).

KEGG REACTION serves as the database for chemical reactions found in metabolic maps and distinctive enzymatic reactions, each with its unique identification number in the database (Shulipa et al., 2020).

**Using the EAWAG-BBD bioinformation electronic database.** Methane, a biogenic gas, is biologically produced from carbon dioxide through methanogenesis, involving 2-electron reductions. Methanogens worldwide generate 1,015 grammes of methane annually, according to the EAWAG-BBD. The interconnectedness of methanogenesis and methanotrophy plays a crucial role in the Earth's C1 metabolic cycle, facilitating the transformation and cycling of C1 compounds. According to Shulipa et al. (2020), this process involves the breakdown and assimilation of C1 fragments by various microorganisms, contributing to the dynamics of the global C1 cycle. The study of these reactions elucidates the principles of biocatalysis, which are essential for understanding the processes of chemical production and biodegradation of environmental contaminants. This includes detailed insights into the metabolic pathways, the chemicals involved at each stage, the microorganisms responsible for these transformations, as well as the relevant enzymes and genetic information (About the EAWAG Biocatalysis, 2014).

**The BacDive bioinformation database** offers a comprehensive repository of information on bacteria and archaea, supporting research into biodiversity among these organisms. This resource is particularly valuable for identifying species that play roles in the anaerobic digestion process, facilitating the search for data on their optimal cultivation conditions in technological applications. The BacDive platform also allows for the exploration of nutrient media, including those with varying compositions of trace elements (BacDive Dashboard, 2022). Additionally, it provides access to taxonomic directories and tools to determine the locations of inoculum selection and analyse their adaptive capacity to changing environmental conditions.

## RESULTS AND DISCUSSION

### Bioeconomy strategy for the growth of industrial sectors

Biotechnology as a tool for achieving economic realisation has its own sectoral division for application in various economic spheres.

According to the international classification, biotechnologies have been established to be distinguished by colour: green (agricultural and environmental biotechnology, including the production of biofuels and biofertilizers); red (biopharmaceuticals, biodiagnostics); white (industrial biotechnology); blue (marine biotechnology, aquaculture); gold (bioinformatics, nanobiotechnology); brown (biotechnology for deserts and arid areas); grey (bioprocesses and fermentation); black (bioterrorism, biological weapons) (Barcelos et al., 2018).

The diversity observed in bioeconomic cluster settings highlights the importance of developing specific regional circular bioeconomy strategies, taking into account local strengths and weaknesses, while avoiding 'oneshot' solutions for individual industry technologies. In addition, research into product and technology design, together with end-of-life strategies for bioproducts, are important elements of the systems. To optimise the potential, clear time-bound milestones are needed that not only promote the development of the bioeconomy as a whole, but also focus on enabling technologies and cascade pathways that promise the greatest potential for utilisation and emission reductions (OECD et al., 2009). It is gradually expanding its sphere of influence on the economies of different countries. Its influence is projected to increase globally starting in 2030 (Fig. 4).

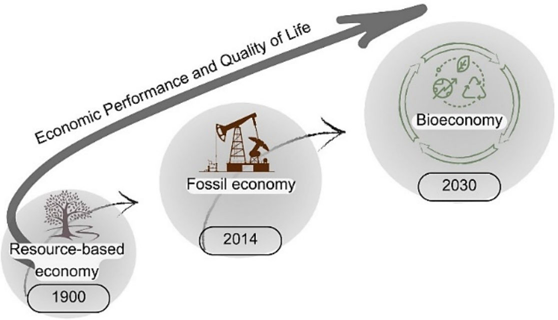

**Figure 4.** The bioeconomy will be the next wave of economy.

The global dynamics of biotechnology sector development is shown in Fig. 5.

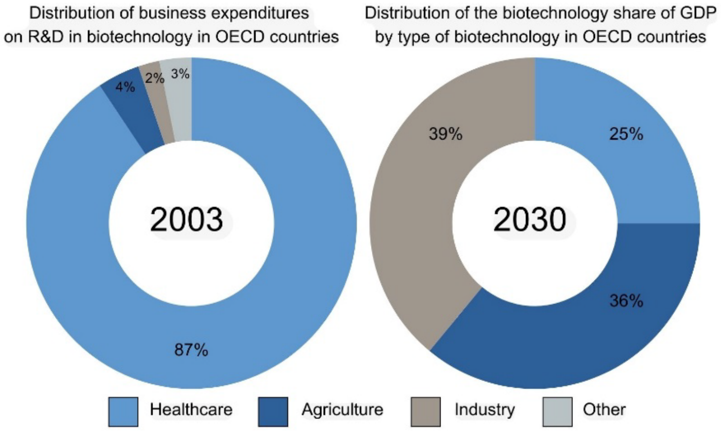

**Figure 5.** Comparative diagram of the distribution of business R&D expenditures and GDP share by type of biotechnology.

The circular economy aims to change the classical linear model of production by focussing on products and services that minimise waste and other types of pollution. The interdependence between the bioeconomy, green economy, and circular economy is shown in Fig. 6.

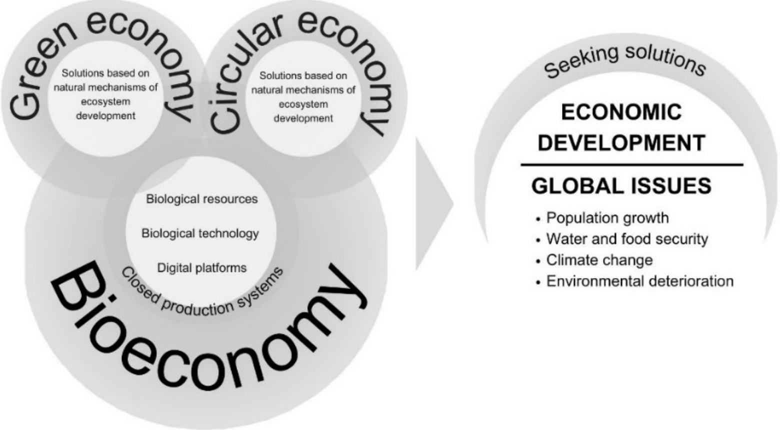

**Figure 6.** Diagram of dependencies between different economic concepts.

One example of the development of the bioeconomy in the world is bioenergy. Its structure is shown in Fig. 7. Experts estimate that proven oil reserves last for 40–50 years; gas reserves for 80 years; and coal reserves for about 400 years (Statistical Review of World Energy, 2021). Furthermore, the trend of rising gas prices over the past 10 years has increased rapidly, which is an economic prerequisite for the active development of bioenergy.

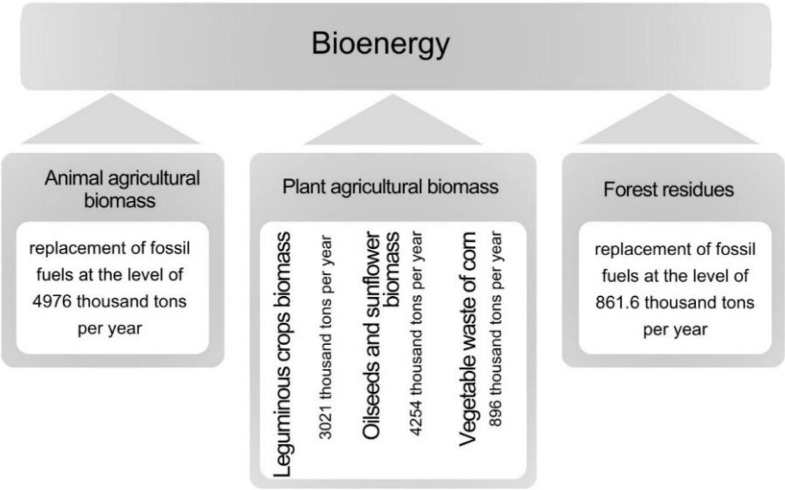

**Figure 7.** Structure of bioenergy.

Efficiency of sustainable development of the bioeconomy:

- environmental efficiency: minimizing the impact of production processes on the environment; promoting the conservation and restoration of biodiversity in agricultural landscapes; promoting the conservation and restoration of soil fertility; protecting water resources from pollution.
- economic efficiency: gradual increase in the natural productivity of agrocenoses and soils; reduction of production costs due to the refusal to use expensive chemicals and reduction of energy intensity of production; increase in product competitiveness;
- social efficiency: creation of additional jobs in rural areas; creation of new prospects for small and medium-sized farms.

The basis of domestic agricultural development's environmental policy should be rooted in ensuring its environmental safety through the adoption of green production practices. The greening of agricultural production should be understood as a process that involves combining and cooperating a set of innovative technologies in the sectors aimed at economic growth of the industry and environmental protection as interdependent and complementary elements of strategic agricultural development, which will guarantee high quality food to the population. The sustainable development of agriculture based on the green economy is possible through the use of alternative technologies that are environmentally friendly and ensure increased productivity in harmony with the ecosystem (Gollier et al., 2019). The effectiveness of the implementation of the green economy in agricultural production is confirmed by the following performance indicators:

- reduction of soil structure and compaction through agrotechnical measures;
- scientifically based application of agricultural land reclamation;
- reduction of nutrient losses in the soil;
- reducing chemical load through the use of environmentally friendly fertilisers;
- use of scientifically based crop rotations;
- introduction of environmentally friendly biologically based crop production technologies;
- introducing environmental certification and environmental labelling.

## Biowaste as a sustainable feedstock for energy production within the framework of bioeconomy promotion

In general, the application of life cycle assessment to waste management systems has great potential, especially to support the decisions of planners and companies involved in waste collection, transportation, and disposal.

The principles of bioeconomy encourage the sustainable use of recycled nutrients and the transformation of conventional systems into sustainable ones to minimise environmental impacts. Thus in Fritzen Cidón et al. (2023) is presented how bioeconomy principles are applied for socio-ecological benefits to Brazilian organic farmers (in the region of Vale do Rio do Sinos, Rio Grande do Sul). The bioeconomic principles applied by Brazilian organic farmers have had a positive socio-ecological impact. Nevertheless, there is still a need for more assistance in the bioeconomy approach, adoption of cleaner technologies and independence of external suppliers without organic guarantees.

The idea of clean and affordable renewable energy sources has led the industry to focus on the development of biorefineries for a sustainable bioeconomy in Dvoretsky et al. (2022). Therefore, microalgae characterised by versatile metabolism, hold significant potential for the generation of beneficial substances across a range of applications, including pharmaceuticals, food and feed supplements for animals and fish, materials, biofertilizers, and biofuels.

Lignocellulosic biomass (LCB) is considered as a widely available and stable feedstock for biofuel production, with Yadav et al. (2023) emphasizing that through the implementation of diverse conversion technologies, an integrated LCB bioprocessing platform can be established, embodying the principles of a ‘circular bioeconomy’.

Several technical challenges must be considered to ensure the sustainability of the biofuel economy for commercialisation (Hasan et al., 2023).

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

Infrastructure development is a challenge to the growth of the biofuel economy. The tendency of the public to transition from fossil fuels (gasoline and diesel) to biofuels in the road transportation sector is important for the successful implementation.

Enhancing farming practices to increase feedstock quality and yields, as well as appropriate infrastructure, including electricity, roads and water, also require further development.

The advancement of the bioenergy economy requires overcoming several challenges related to competition for agricultural land, rising food prices, difficulties in technological progress, and obstacles in infrastructure development (Hasan et al., 2023).

Many studies focus on a limited set of indicators that do not cover the full range of impact categories in understanding the ‘Bioeconomic Footprint’. Furthermore, the majority of research is concentrated either on partial industry coverage within the bioeconomy or on assessing the overall economic impact without disaggregating sectors based on biotechnology (Sinkko et al., 2023).

The specificity of certain research focuses also prevails in a number of studies. For example, Cao et al. (2023) summarise recent advances in the application of biofertilizers derived from microalgae in agriculture. This represents a particular area within the agricultural sector, contributing to the development of the circular bioeconomy concept and the goals of sustainable development.

Additionally, anaerobic digestion can be used as a part of a larger bioprocessing system for the production of biofuels, biochemicals and fertilisers, potentially playing a central role in the emerging circular bioeconomy. It is necessary to assess long-term impacts and explore potential accumulations of specific undesired substances. In general, environmental risks are highly dependent on the input feedstock and the digestate produced. Comprehensive purification processes must be developed, as they can both minimise risks and improve economic prospects (Feng et al., 2023).

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. (2023) show that using municipal biowaste methanogenesis to generate electricity is associated with a 25.3–26.6% reduction in CO2 emissions compared to a baseline scenario with conventional electricity generation. This reduction is attributed to the fact that $CO_2$ emissions from renewable sources, including biogas combustion, are not included in the emissions trading quota rules. However, the average national emissions factors used in this calculation are relatively high when compared to the reduction factors stipulated by the Directive (EU) 2018/2001 of the European Parliament and Council, dated December 11, 2018, on the promotion of the use of energy from renewable sources. 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.

In general, the agricultural support system in developed market economies is largely associated with state price regulation, including the establishment of maximum and minimum price thresholds and the setting of indicative or conditional pricing. Such regulatory measures are implemented through the buying or selling of goods (known as commodity intervention). In addition, EU agricultural policy uses such a tool as quotas to regulate the agricultural market. Its essence lies in the fact that maintaining prices for products leads to their overproduction, so quotas are introduced for the production of certain types of products (milk, sugar, alcohol, starch) in order to maintain high domestic prices, prevent overproduction, and reduce costs from the EU budget (EU budget: the Common Agricultural Policy beyond 2020, 2018).

The Fig. 8 groups the main factors influencing the process of biowaste valorisation taking into account the environmental factor, based on data from Mishra et al. (2023).

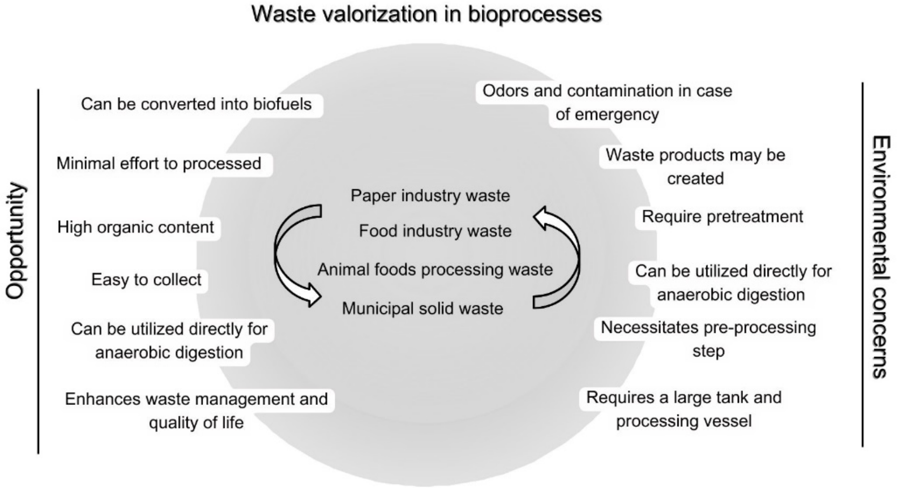

**Figure 8.** Environmental factors of waste valorisation in bioprocesses.

There are several significant obstacles associated with the boundaries of the LCA system that continue to pose challenges for biowaste management. In Mishra et al. (2023) The concept of ‘waste to wealth’ aims to create a future sustainable lifestyle where waste is valued for its environmental benefits and the development of new technologies, livelihoods and jobs.

We propose a roadmap for technology modernisation based on the example of the anaerobic waste conversion process as part of the implementation of the circular bioeconomy (Fig. 9).

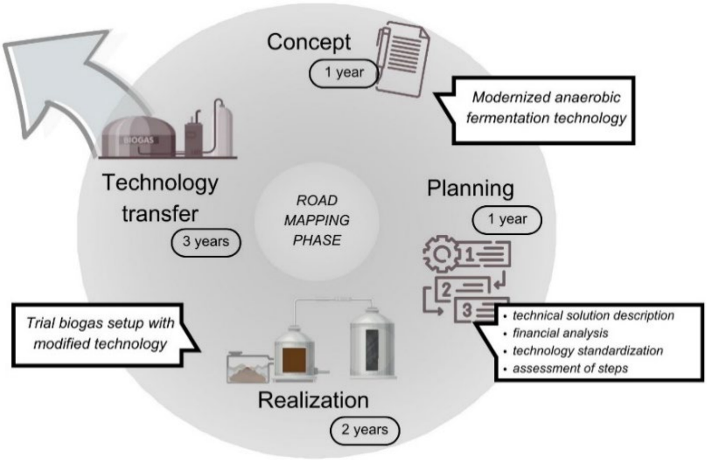

**Figure 9.** Phases of the roadmap for the modernisation of bioenergy technologies in the sectoral implementation of the principles of circular bioeconomy.

The first step is to identify the biotechnology sector for implementation, with a review and search for innovative solutions for implementation. The next stage is the development of a technological solution with visualisation of the necessary equipment. This phase involves conducting initial pilot experiments and modelling the results on the basis of the data obtained. Based on the results of successful process modelling, the finished concept is transferred to the planning stage before its full-scale implementation and direct implementation in the field of application, in our example, in the field of renewable energy with organic waste processing (Barretti et al., 2021; Luz et al., 2021). However, there are many challenges that need to be addressed to make biowaste fermentation (sustainable feedstock) sustainable for the commercial production of value-added products such as biofuels and biochemicals. More detailed determination of the optimal operating conditions for enzymes and fermenting microorganisms is needed, as well as the effect of biostimulant additives on their metabolic activity. Integrated microbial and enzyme engineering is a powerful approach to improve the efficiency of fermentation processes by improving the tolerance of microorganisms and enzymes to different pH and temperature conditions. Another important aspect is the scale-up of the fermentation process, which is also related to the evaluation of return on investment. which is important for the development of economically and environmentally sustainable processes. In addition, the properties and supply of raw materials, as well as the availability of skilled labour, must be considered (Verardi et al., 2023).

### Evaluation of a mineral additive phosphogypsum for use in bioproduction

Phosphogypsum consists primarily of calcium sulphate dihydrate ($CaSO_4 \cdot 2H_2O$) and contains impurities of undecomposed phosphate, phosphoric salts and silicates. The amount of impurities present is influenced by factors such as the mineral composition of the feedstock, production efficiency and equipment serviceability, as well as technological discipline, etc.

The results of the X-ray microanalysis of the phosphogypsum sample are shown in Table 1.

Phosphogypsum, containing calcium, phosphorus, sulphur, and various microelements, can be used for the chemical reclamation of soils, including those with Sandy compositions. Its utilization enhances the soil's physical properties, primarily through the enrichment with $Ca^{2+}$ cations, as indicated (Nayak et al., 2013).

In samples of phosphogypsum taken directly from the production process, the following metals were detected by XRF analysis (in % of total weight) Fe (0.010%), Ni (0.001%), Cu (0.003%).

**Table 1.** Chemical composition of phosphogypsum (dried at 333 K)

| Type of green area | % of total weight |
|---|---|
| CaO | 38.73 |
| $SO_3$ | 39.22 |
| $SiO_2$ | 1.79$^{2}$ |
| $P_2O_5$ | 0.45$^{2}$ |

In our previous studies (Plyatsuk & Chernish, 2014), phosphogypsum was used as a low-soluble sulphur-containing mineral additive in the process of biosulfide utilisation of biowaste, which is consistent with the studies of other authors Bounaga et al. (2022).

The use of phosphogypsum in the biowaste treatment process has the following advantages

- cheap raw material base (sustainable feedstock);
- significant prevalence of this type of waste;
- enrichment with microelements;
- sulphur compounds contained in PG can be freely used by sulphate reducers as a mineral substrate for their growth and hydrogen sulphide formation, due to the high affinity of microbial cells for sulphate/sulfite ions;
- reducing the technogenic load of phosphogypsum waste on the environment.

Mechanisms of transition of HM from organomineral complexes to the liquid phase:

- In the process of mineralisation, metal-organic complexes are transformed into soluble simple organic compounds under the influence of a biological agent and HM ions are released into solution;
- HMs that form salts with compounds of the organic component of sediments are exchanged for Ca2+ on the surface of calcium material, such as phosphogypsum, by the mechanism of ion exchange. Thus, this leads to the formation of calcium compounds with organic structures of biowaste.

After the transition to the liquid phase, the HM ions interact with biogenic hydrogen sulphide. Hydrogen sulphide serves as a strong reducing agent, which contributes to the reduction of HM to reductive forms.

It should be noted that sulphate reducers are also present in the association of microorganisms during anaerobic digestion. Several works consider the competitive interrelationships of sulphate-reducing bacteria and methanogenic archaea (Oliveira et al., 2021; Sela-Adler et al., 2021). However, *sulphate-reducing* bacteria and *methanogens* may also be present in symbiotic relationships. Therefore, this work substantiated that through L-cysteine, methane metabolism participated in the sulphide consumption process, which is involved in cysteine and methionine metabolism, promoted the direct reaction of sulphide formation and regulated environmental conditions (pH and $S_2$ concentration) for the symbiosis of sulphate reducers and methanogens (Shi et al., 2020). Consequently, the system was searched and the pathways for methane and sulphur metabolism were identified, as shown in Fig. 10.

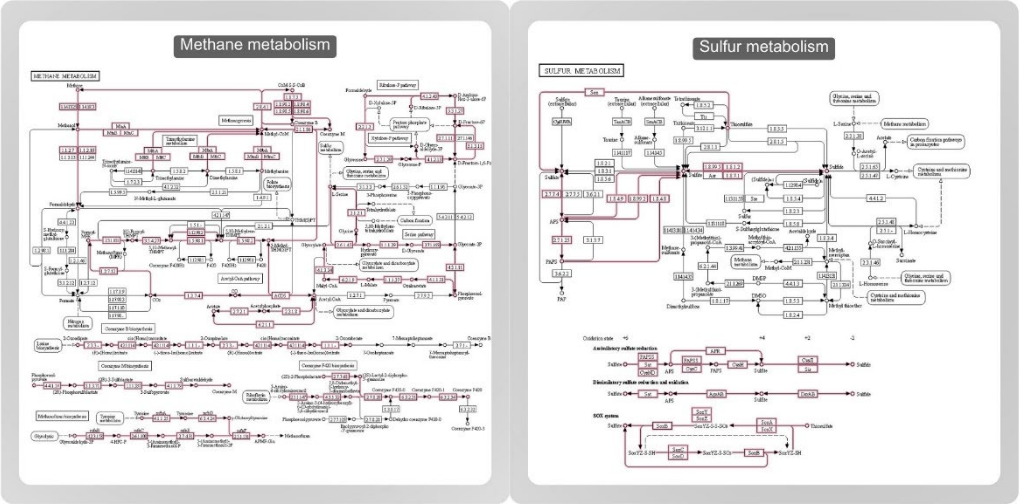

**Figure 10.** Search for dominant methanogenic species on the interactive map of methane production and sulphur metabolism. (based on KEGG PATHWAY: map00680; KEGG PATHWAY: map00920).

Fig. 10 delineates the crucial mechanisms by which methane and sulphur are metabolised within the microbial community, highlighting the pivotal roles of methanotrophs, methanogens, and methylotrophs in the carbon cycle. Methanotrophs are shown as the primary consumers of methane, whereas methanogens are depicted as the producers of methane through anaerobic processes, utilizing three distinct pathways, with CoM serving as the essential methyl carrier. These include the conversion of $CO_2$ to methane, methanol to methane, and acetate to methane. Furthermore, Fig. 10 demonstrates how the methane oxidation processes in methanotrophs and methylotrophs produce formaldehyde, which is then funnelled into three separate pathways for energy production and biosynthesis, including the metabolism of trimethylamine by methylotrophs (KEGG PATHWAY: map00680). With respect to sulphur metabolism, the diagram outlines its significance in the global sulphur cycle, illustrating both the assimilatory pathway, which incorporates sulphate reduction for amino acid synthesis without releasing sulphide, and the dissimilatory pathway, where sulphate serves as a terminal electron acceptor in anaerobic organisms, leading to the production of inorganic sulphide. The early stages of both pathways involve the activation of sulphate. Additionally, Fig. 10 shows the SOX system for sulphur oxidation, present in various bacteria and archaea, including those that oxidise sulphur compounds through photosynthesis. It also touches upon chemolithoautotrophic sulphur oxidizers that may invert the enzymes for dissimilatory sulphur reduction, creating a pathway for sulphur oxidation (KEGG PATHWAY: map00920).

The following is a text map of the methanogenesis pathways (Fig. 11), which outlines how a specific organism initiates the pathway, with later stages conducted by additional organisms. For more in-depth information regarding specific compounds or reactions, interactive links are accessible through a 40k graphical format map hosted on the KEGG database. Additionally, the map delves into the role of microorganisms in the dissimilatory reduction of sulphate, providing essential insights necessary for understanding the impact of phosphogypsum as a mineral supplement in optimising the anaerobic digestion process.

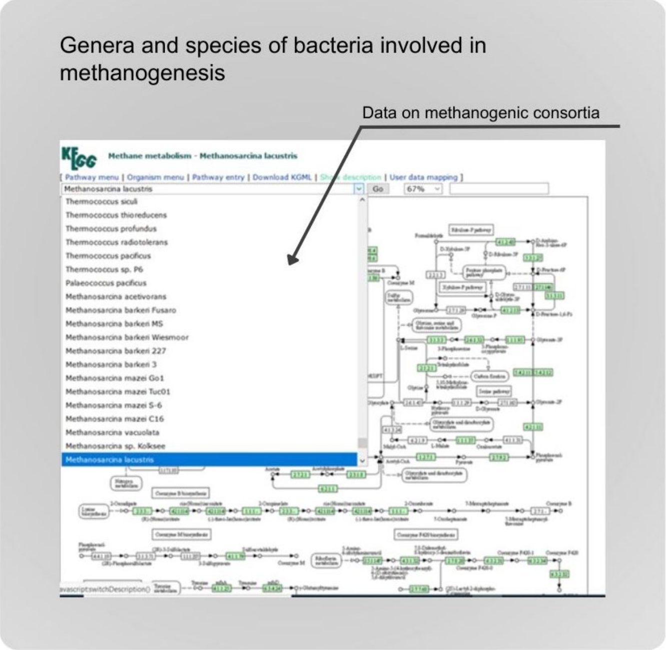

**Figure 11.** Web page displaying the necessary types and species of bacteria involved in the process of methanogenesis in a unified community (based on KEGG PATHWAY: map00680).

Thus metabolic pathways of sulphur-reducing microorganisms were analysed according to the KEGG database, BacDive, EAWAG-BBD, and their species were grouped, which can be effectively used for the detoxification of industrial wastewater and sewage sludge in the process of their anaerobic digestion with the addition of phosphogypsum (Table 2).

General view of the reaction of precipitation of heavy metal ions by hydrogen sulphide

$$b1_S SH^- + b1_{Me} Me^{n+} + b1_{SO} SO_4^{2-} \rightarrow b1_{MeS} MeS + b1_H H_2O, \qquad (1)$$

where $b1_S, b1_{Me}, b1_{SO}, b1_{MeS}, b1_H$ are stoichiometric coefficients; $Me^{n+}$ is ions $Cd^{2+}$, $Cu^{2+}$, $Fe^{2+}$, $Fe^{3+}$, $Zn^{2+}$, $Cr^{3+}$, $Ni^{2+}$.

The main organic substrate at the final stage of organic matter decomposition is acetate. If the anaerobic oxidation of organic matter is not complete, acetic acid accumulates as the final product and the environment in the bioreactor is acidified.

Additionally, during sulfidogenesis, a biological reduction of phosphates occurs, which has been confirmed by previous studies (Plyatsuk & Chernish, 2014):

$$Fe_3(PO_4)_2 + 3SO_4^{2-} + 6C_{org} \rightarrow 3FeS \downarrow + 2PO_4^{3-} + 6CO_2, \quad (2)$$

where $C_{org}$ is organic substrate.

**Table 2.** Characteristics of sulphur-reducing microorganisms

| Species | Temperature range | Note | Link |
|---|---|---|---|
| *Desulfovibrio* | mesophilic | Desulfobaculum senezii CVL (species Desulfovibrio senezii) is an anaerobe, mesophilic bacterium that was isolated from solar saltern | https://bacdive.dsmz.de/strain/4136 |
| *Desulfonema* | mesophili | Desulfonema ishimotonii DSM 9680 is an anaerobe, mesophilic bacterium that was isolated from marine mud | https://bacdive.dsmz.de/strain/3991 |
| *Desulfomicrobium* | mesophilic | Desulfomicrobium aestuarii ADR26 is an anaerobe, mesophilic bacterium that was isolated from sediments | https://bacdive.dsmz.de/strain/4061 |
| *Desulforhabdus* | mesophilic | Desulforhabdus amnigena ASRB1 is an anaerobe, mesophilic bacterium that was isolated from sludge, UASB reactor | https://bacdive.dsmz.de/strain/16675 |
| *Desulfomonile* | mesophilic | Desulfomonile tiedjei DCB-1 is an anaerobe, mesophilic bacterium that was isolated from sewage sludge | https://bacdive.dsmz.de/strain/16666 |
| *Desulfarculus* | mesophilic | Desulfarculus baarsii Konstanz is an anaerobe, mesophilic bacterium that was isolated from ditch mud | https://bacdive.dsmz.de/strain/17627 |
| *Desulforegula* | mesophilic | Desulforegula conservatrix Mb1Pa is an anaerobe, mesophilic bacterium that was isolated from sediment from a shallow freshwater eutrophic lake | https://bacdive.dsmz.de/strain/3992 |

In this process, phosphate and hydrophosphate anions bind to Ca2+ cations to form various modifications of calcium phosphates, which precipitate due to their low water solubility. Additionally, part of the phosphate ions is displaced from the biotechnology system when it passes into the liquid phase. This also corresponds to the results obtained by other authors (Matsuura et al., 2021, Diao et al., 2023).

During the precipitation of hydrogen sulphide and HM ions in the form of sulphur, the microbial community works stably (Diao et al., 2023; Qin et al., 2024; Melgaço et al., 2020).

In the process of such treatment, a number of biochemical transformations of the components of the waste mixture occur, which is consistent with other research findings (Matsuura et al., 2021; Almuslamawy et al., 2023; Bounaga et al., 2023):

- biological reduction of phosphates, with a significant portion of the released phosphate ions chemically bonding with calcium and partially passing into the liquid phase;
- calcium carbonate is formed due to the release of carbon dioxide in the system;
- during the breakdown of protein compounds, ammonia is released and combined with sulfate ions, forming ammonium sulfate;
- complex compounds with HM (HM salts with organic compounds) are destroyed in the course of microbiological processes, HM ions pass into the liquid phase, where they interact with biogenic hydrogen sulphide to form stable metal sulphide compounds.

The prospect of industrial implementation in the field of integrated processing of persistent raw materials (biowaste and phosphogypsum) is one of the directions of the realisation of the sectoral bioeconomy. In our further research, we will develop a methodology of synergy of these wastes (as sustainable feedstock) on the basis of biochemical processes of their joint processing with the possibility of implementation in bioenergy and agriculture.

## CONCLUSIONS

The analysis focusses into global advancements in bioeconomy development, particularly within the bioenergy sector. A breakdown of the bioenergy structure is provided, along with a proposed roadmap for the modernisation of biotechnology, exemplified by the anaerobic digestion process, aimed at promoting the principles of circular bioeconomy. Additionally, the integration of anaerobic digestion into broader bioprocessing systems is explored, highlighting its role in biofuel, biochemical and fertiliser production within the circular bioeconomy framework.

The stages of this modernisation roadmap are examined within the implementation of sectoral circular bioeconomy, focussing on efficiency indicators relevant to the integration of bioeconomy practices into agricultural production.

Furthermore, attention is drawn to a vital synergy between anaerobic technologies and the agricultural sector: the enrichment of digestates with essential macro- and microelements facilitated by mineral additives. Utilisation of the compositions of the components of phosphogypsum by various microorganisms is assessed through bioinformation databases, underscoring the importance of environmental sustainability in this context. In further studies, the application of phosphogypsum in bioprocesses will be deepened by biotesting. Possible applications of nanomaterials will also be considered.

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