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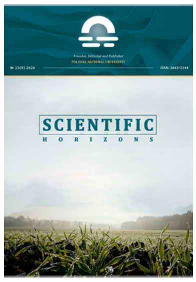

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Bioeconomy as a strategic direction for sustainable development of the agricultural sector

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Abstract. The study aimed to identify the key principles of bioeconomy and their impact on the environmental, economic and social sustainability of the agro-industrial complex. A comprehensive analysis of existing practices of applying Environmental, Social, Governance (ESG) strategies and bioeconomy in the agricultural sector, including the study of successful cases and a comparative analysis of the effectiveness of innovative technologies, was conducted. The study determined that the introduction of bioeconomy principles in the agricultural sector significantly contributes to strengthening the sustainability and efficiency of the agricultural sector. Between 2021 and 2024, there was an increase in the area used for sustainable agriculture, from 43 to 47 million hectares, as well as an increase in the share of organic fertilisers in the total, from 5% to 7%. The use of drip irrigation has also increased, from 1.5 to 3 million hectares. At the same time, food losses in the agricultural sector decreased from 16% to 13%, and the efficiency of water use increased from 3.5 to 4 km^3. The development of circular technologies has brought significant results: the share of recycled waste in agricultural production increased from 22% to 30%, and the number of companies using such solutions increased from 90 to 150. The use of biotechnology has also had a positive impact – the share of GM crops has increased from 5% to 9%, and the carbon footprint has been reduced from 5 to 3 million tonnes of CO_2. A study of the successful implementation of ESG approaches in agribusiness, including in Kazakhstan, Germany and the Netherlands, showed a reduction in the use of chemical fertilisers, improved product quality and reduced greenhouse gas emissions. For instance, Olzha Agro reduced the use of agrochemicals by 12% while achieving an 18% increase in yields. EcoMilk has reduced its CO_2 emissions by 25% by

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using biodegradable packaging and installing solar panels. In general, the results of the analysis confirmed the importance of integrating bioeconomic and ESG principles for the sustainable development of the agro-industrial complex and increasing its social significance

Keywords: ecological footprint; precision agriculture; circular economy; biofermentation; ESG strategies

INTRODUCTION

The bioeconomy is becoming increasingly strategic for the sustainable development of the agricultural sector. It is central in ensuring food security, increasing agricultural productivity and minimising the negative impact on the environment. In the context of global climate change, growing demand for food and limited natural resources, the transition to a bioeconomic model of production and consumption is not just relevant, but vital. The bioeconomy is based on the rational use of renewable bioresources, the introduction of advanced biotechnologies and the application of closed (circular) cycle principles, which provides environmentally friendly and more efficient production. Integration of Environmental, Social, Governance (ESG) approaches (environmental, social and governance aspects) is also important, as they help to reduce the carbon footprint, improve working conditions and ensure transparency of management in the agricultural sector.

In the context of climate change and the need to move to a bioeconomic model, the problem of sustainable development of the agricultural sector is relevant. N. Khan *et al.* (2021) emphasised that the use of innovative agricultural technologies has significantly increased the sustainability of crops and reduced dependence on chemical fertilisers. The study demonstrated how modern technologies not only increase yields but also reduce the environmental impact of agricultural production. J. de Carvalho *et al.* (2022) addressed the use of renewable bioresources, such as biofuels and biopolymers in the agricultural sector, defining them as substantial for the reduction of the carbon footprint and strengthening the sustainability of production systems. A similar was highlighted by N. Patel *et al.* (2022), emphasising the role of biotechnology in shaping sustainable agricultural production models. The authors emphasised the importance of using biopolymers and biofuels to reduce pressure on the ecosystem and increase economic profitability. B. Koul *et al.* (2022) consider the principles of the circular economy as strategically important for agricultural waste management. The study suggested ways to recycle agricultural waste, such as biogas and compost, to create closed production cycles and minimise losses. P. Singh and A. Sharma (2022) analysed the introduction of precision farming technologies, including drones and Internet of Things (IoT) systems. Following the study, such solutions can significantly increase the efficiency of the agricultural sector and reduce its environmental impact.

A. Gamage *et al.* (2023) highlighted the important role of organic farming in improving soil condition and reducing chemical pollution. The study emphasised the resilience of organic practices to changing climatic conditions. U. Hafeez *et al.* (2023) analysed the use of genetic engineering to develop plant varieties that are resistant to climate stress. Following the study, such varieties can significantly increase crop yields and the adaptability of agricultural production to adverse conditions. R. Azis *et al.* (2024) considered biofermentation as a potential method for producing environmentally friendly feed and fertilisers. The study demonstrated that these technologies reduce the need for chemical additives and improve the quality of agricultural products. J. Ramos-Teodoro *et al.* (2021) emphasised the importance of introducing solar panels and other renewable energy sources in the agro-industry, demonstrating how such solutions contribute to reducing energy consumption and carbon emissions. K. Refsgaard *et al.* (2021) studied the social dimension of the bioeconomy, particularly its impact on job creation and improving working conditions in rural areas. The study highlighted the role of the bioeconomy in strengthening social stability and rural development. However, there are still unresolved issues related to the limited attention paid to the social aspects of the bioeconomy, including employment and the improvement of working conditions in rural areas. In addition, specific mechanisms for integrating biotechnology into various agricultural systems have not been well developed, indicating a need for further scientific research in this area.

The study aimed to analyse the application of bioeconomy principles in agribusiness, identify successful examples of their implementation and assess the impact of these approaches on sustainable agricultural development.

MATERIALS AND METHODS

The study analysed and evaluated the main components of the bioeconomy and sustainable development of the agro-industrial complex in the context of the introduction of innovative technologies and principles of sustainable agriculture, based on data covering the period from 2021 to 2024. The study addressed the efficient use of bioresources to improve crop sustainability and yields. The research analysed innovative agricultural technologies, including new biotechnologies and environmentally friendly fertilisers, which improve product quality and reduce negative environmental impact. The study also analysed ways to use biodegradable fertilisers and biological products to reduce soil and water pollution. Data on the area under sustainable agriculture, the share of organic fertilisers, the use of drip irrigation, levels of food losses and water efficiency were studied (according to the Bureau of National Statistics Agency for Strategic planning and reforms of the Republic of Kazakhstan (n.d.)).

The study also analysed the principles of circular economy and waste-free production in the agro-industrial complex. The processes of recycling agricultural waste, such as biogas and compost, as well as the use of agricultural by-products to produce biofuels and biopolymers, were considered. Data were analysed on the share of recycled waste, the volume of recycled organic materials, the number of enterprises that have implemented circular technologies, as well as the use of by-products and emission reductions in the agricultural sector (Ministry of Industry and Construction of the Republic of Kazakhstan, 2024). The study examined biotechnologies, including genetic engineering methods for creating resistant plant varieties, as well as biofermentation and biocatalysis for developing new feeds, fertilisers and food additives. Data on the share of genetically modified crops, the production of biotechnology products, the reduction of the carbon footprint in agricultural production, and the use of biotechnology to increase yields and reduce dependence on chemical fertilisers were analysed (Ministry of Ecology, Geology and Natural Resources of the Republic of Kazakhstan, 2021).

The study analysed the reduction of the carbon footprint. Precision farming technologies, such as drones, Iot and Big Data, which optimise the use of resources in agriculture and reduce carbon emissions, were addressed. The growth of organic farming and the use of alternative energy sources, such as biogas and solar panels, to reduce carbon emissions and minimise the climate impact of the agricultural sector were also analysed. As part of the analysis, examples of Kazakhstani companies Olzha Agro (n.d.) and EcoMilk (n.d.) were considered, which demonstrate the introduction of precision farming technologies, increased yields, reduced use of agrochemicals, reduced CO_2 emissions and the use of renewable energy sources. Foreign cases were also studied: the German company BioEconomy Cluster (n.d.) and the Dutch company Van der Knaap (Reiley, 2023). Additionally, examples of other Kazakhstani enterprises involved in the development of the bioeconomy were analysed. In particular, the activities of Zharkent Starch Packing Plant (n.d.), which processes agricultural raw materials into feed additives, Biofert (n.d.), a producer of bio-organic fertilisers, and Agrofarm (n.d.), an agricultural enterprise that implements sustainable agricultural technologies.

The projects in the field of bioenergy implemented by Partner-Agro (n.d.) and Zorg Biogas (n.d.), the activities of KazAgro Green (n.d.) in the field of environmental innovation, as well as eco-packaging solutions from GreenPack (n.d.) were studied. The role of the KazAgro-Expo exhibition (n.d.) as a platform for agricultural innovation, fermentation of feed in Kostanay region (Agro-Bio-Auliekol, n.d.), development of enzyme complexes at the National Centre for Biotechnology (n.d.), digitalisation of rural areas (Digital Villages of…, 2020), and renewable energy projects by Farmers of Chilik (n.d.) were analysed. The analysis included official data from the Ministry of Agriculture of the Republic of Kazakhstan (n.d.) on the growth of organic land, research on the use of *Trichoderma* as a biofungicide (Yerpasheva *et al.*, 2022), and social aspects of the bioeconomy presented in Astana TV reports (Under the "Green…, 2019). These companies were selected for their successful application of bioeconomic technologies, such as agricultural waste recycling and vertical farming, which have significantly improved the environmental and economic efficiency of their farms. Their selection was based on their leading positions in agricultural innovation and sustainable environmental approaches.

RESULTS

The bioeconomy is a system of economic activity based on the use of renewable biological resources, advanced biotechnologies and circular production principles. In the agro-industrial complex, it plays a key role in ensuring food security, improving agricultural efficiency and reducing environmental impact. At the end of 2022, the permanent rural population in the Eurasian Economic Union countries was about 52 million people, accounting for 28% of the total population of the region. The total area of agricultural land in the same year was 112.7 million hectares, of which 59.4% was occupied by cereals and legumes. Agricultural production in 2022 grew by 10.4% compared to 2021, reaching USD 166 billion (Fernández-Puratich *et al.*, 2021).

Implementation of ESG principles in the agricultural sector contributes to the sustainable development of the industry, reduction of negative environmental impact, improvement of social conditions and increase of management transparency. 70% of companies in the agricultural sector recognise the importance of the environmental component, of which 80% implement projects for waste recycling and reduction, and 77% focus on energy efficiency. Social aspects of ESG are covered by 74% of companies, of which 96% develop the skills and competences of their employees, and 92% provide decent remuneration for labour. The managerial part of ESG is covered by 72% of companies, of which 90% are devoted to the reduction of business risks and 80% monitor compliance with ethical standards. This data confirms that the integration of ESG principles into corporate strategies contributes to their sustainable development and increased competitiveness in the agricultural sector (Leite de Almeida *et al.*, 2024). In the context of global challenges such as climate change, depletion of natural resources and the need to ensure food security for a growing population, the effective use of biological resources is becoming one of the key tasks for the agro-industrial complex (Akanmu *et al.*, 2023). Modern agricultural technologies are the foundation of sustainable agriculture, as they not only increase crop yields but also contribute to improving crop resilience. These innovations support the agricultural sector in adapting to changing environmental conditions while reducing negative impacts on the ecosystem (Table 1).

***Table 1**. Rational use of biological resources in the agricultural sector of Kazakhstan*

Metric	2021	2022	2023	2024
Area of agricultural land used for sustainable farming (million hectares)	43	44	45	47
Share of organic fertilisers in total volume (in %)	5%	5.5%	6%	7%
Application of drip irrigation technologies (million hectares)	1.5	2	2	3
Level of food losses in agricultural sectors (in %)	16%	15%	15%	13%
Water use efficiency (km^3)	3.5	3.6	3.8	4

***Source:** compiled by the authors based on the Bureau of National Statistics Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (n.d.)*

The agro-industrial complex is showing positive dynamics in various aspects of sustainable development. The area of agricultural land used for sustainable farming is increasing, reflecting the growing interest in environmentally friendly farming methods. The share of organic fertilisers is also growing, reflecting a desire to reduce dependence on chemicals. At the same time, drip irrigation technologies, which contribute to more efficient use of water resources, are becoming increasingly popular. Food waste is decreasing, which may indicate improvements in logistics and processing. All of these changes are aimed at increasing environmental sustainability and more efficient use of natural resources in agricultural production. In Kazakhstan's agricultural sector, the development of new agricultural technologies is manifested through the introduction of IoT-based soil moisture monitoring systems, the use of Netafim precision irrigation systems, and the use of DJI AGRAS drones for the precise application of fertilisers and plant protection products. These technologies reduce water consumption by 25-40%, and the dosage of agrochemicals is optimised depending on the actual soil conditions and phytosanitary status of the fields. For instance, Zharkent Starch Packing Plant (n.d.) recorded an 18% reduction in mineral fertiliser costs and a 12% increase in corn yields after implementing drone monitoring and spot fertilisation.

As part of the transition to the sustainable use of bioresources, the practice of using biodegradable fertilisers based on sapropel, peat and fermented plant residues is actively developing. For example, BioFert (n.d.) produces liquid organo-mineral fertilisers obtained using anaerobic fermentation products, which not only improve the physical and chemical characteristics of the soil but also contribute to an increase in humus levels. After two seasons of applying such fertilisers, Agrofarm (n.d.) increased the organic matter content of the soil by 0.3-0.5%, which stabilised winter wheat yields at over 42 c/ha. In addition to fertilisers, biological products based on *Bacillus subtilis*, *Trichoderma harzianum* and *Streptomyces* spp. are actively used as substitutes for chemical fungicides and pesticides in vegetable cultivation. Research by the Institute of Soil Science and Agrochemistry has shown that the use of these biological products in greenhouse farms in the Almaty region reduces tomato blight by 60% and increases the dry matter content of fruits by 8-10%, which improves their market quality. The use of organic fertilisers such as biohumus, compost from agricultural waste and fermented manure shows high carbon efficiency. For example, at the Partner-Agro farm (n.d.), the use of compost from plant residues reduced the carbon footprint per hectare by 1.2 tonnes of CO_2 per season compared to traditional nitrate fertiliser application. This approach not only increases soil productivity but also contributes to the environmental sustainability of agricultural landscapes.

The circular economy, or closed-loop economy, is a model in which waste is recycled into resources, and the production process becomes as sustainable and efficient as possible (Barros *et al.*, 2023). This concept is becoming increasingly relevant in the agro-industrial complex, where traditional production methods often lead to the generation of significant amounts of waste, such as agricultural residues, packaging and chemical emissions. The implementation of circular economy principles in the agricultural sector contributes to a significant improvement in the environmental situation, a reduction in losses and an increase in resource efficiency. This not only minimises the negative impact on the environment but also opens new prospects for creating added value and sustainable growth in the industry (Table 2).

***Table 2**. Circular economy and waste-free production in the agricultural sector of Kazakhstan*

Metric	2021	2022	2023	2024
Share of recycled agricultural waste in agricultural production (%)	22%	23%	25%	30%
Volume of organic waste processed (million tonnes)	1.0	1.2	1.5	2.0
Number of enterprises that have implemented circular technologies	90	100	120	150
Level of utilisation of agricultural by-products (%)	55%	58%	60%	65%
Reduction of waste emissions in the agricultural sector (thousand tonnes)	250	270	300	350

***Source:** compiled by the authors based on the Ministry of Industry and Construction of the Republic of Kazakhstan (2024)*

Improvement in the recycling and utilisation of agricultural waste is notable. The share of recycled waste in agricultural production and the volume of organic materials recycled have been steadily increasing, reflecting improved sustainable production and processing practices in the agricultural sector. The growing number of companies adopting circular technologies also confirms the growing interest in closed production cycles, which contributes to more efficient use of resources and reduced waste. The increased use of agricultural by-products and reduced waste emissions in the agricultural sector indicates improved environmental policies and the introduction of new technologies to minimise environmental impact. These trends support the transition of agricultural production to more sustainable and environmentally friendly models.

One example of the implementation of circular economy principles in Kazakhstan's agro-industrial sector is the construction of local biogas plants for the processing of organic livestock waste. For instance, on farms in the South Kazakhstan region, the company Zorg Biogas (n.d.) has installed bioreactors with a capacity of up to 300 m^3, which use cattle manure and silage residues to produce methane. The biogas produced is used to heat greenhouses and generate electricity, which has reduced coal consumption by 40% during the heating season. At the same time, methane emissions into the atmosphere have been reduced, and energy costs have been cut. Composting of organic residues is actively used in agricultural enterprises in Central Kazakhstan. For instance, KazAgro Green (n.d.) has implemented a multi-stage system of crop residue processing, including shredding, fermentation and maturation of compost with the addition of EM crops. The resulting compost is used on the fields as an organic fertiliser, which has reduced dependence on mineral fertilisers by 25% and increased humus content by 0.4% over two years. This improves the water-holding capacity of the soil and helps to stabilise yields under changing climatic conditions.

Another important area is the production of biopolymers from plant materials. In collaboration with scientists from Nazarbayev University, the start-up GreenPack (n.d.) has developed biodegradable packaging made from corn starch and sunflower husks, which is used to pack seeds and vegetables. This material completely decomposes within 90 days in the soil, leaving no toxic residues. Thanks to such projects, agribusinesses can simultaneously reduce dependence on plastic packaging and their environmental footprint. Modern biotechnologies are substantial in the transformation of the agro-industrial complex, creating new opportunities to improve the quality of agricultural production and increase its sustainability (Rosero-Delgado *et al.*, 2021). Genetic engineering, bio-fermentation, and biocatalysis technologies significantly increase the efficiency of the agricultural sector, making it more adaptable to changing climate conditions, improving product quality and reducing environmental impact. These innovative approaches ensure the sustainability of agriculture in response to global challenges such as climate change, soil degradation and growing food demand (Table 3).

***Table 3**. Application of biotechnology and reduction of carbon footprint in the agricultural sector of Kazakhstan*

Metric	2021	2022	2023	2024
Share of genetically modified (GM) crops (in %)	5%	6%	7%	9%
Production of biotechnology products (million tonnes)	1.0	1.1	1.2	1.5
Reduced carbon footprint in agricultural production (million tonnes of CO_2)	3	3.5	4	5
Use of biotechnology to increase yields (in %)	4%	5%	5%	6%
Reduced use of chemical fertilisers (in %)	3%	4%	4%	6%

***Source:** compiled by the authors based on the Ministry of Ecology, Geology and Natural Resources of the Republic of Kazakhstan (2021)*

There is a gradual increase in the use of biotechnology in agricultural production, which is reflected in the growing share of genetically modified crops and the production of biotechnology products. This not only increases yields but also reduces the carbon footprint of the agricultural sector, which has a positive impact on environmental sustainability. The use of biotechnology to increase yields and reduce the use of chemical fertilisers reflects the desire for more efficient and environmentally friendly agriculture. The introduction of these technologies optimises production processes and minimises the negative impact on the environment, which is substantial in the sustainable development of the agricultural sector. One of the most promising areas of biotechnology in Kazakhstan's agriculture is genetic engineering aimed at creating stress-resistant crop varieties. Since 2021, the KazAgroExpro project (n.d.) has been developing drought-resistant maize and wheat hybrids with integrated DREB1 and CBF genes that activate plant defence mechanisms in the face of water shortages and temperature changes. Field trials in the Zhambyl region have shown that yields of these crops remain at 45-48 cwt/ha at moisture levels below 60% of the long-term norm. This minimises crop losses in the context of climate change and reduces the need for irrigation by 30-35%.

At the same time, the area of biofermentation is developing, especially in livestock production. The Agro-Bio-Auliekol feed mill (n.d.) in Kostanay region has introduced technologies for the microbiological conversion of grain processing waste into high-protein feed additives with a crude protein content of up to 32%. The technology is based on microorganisms of the genera *Lactobacillus* and *Bacillus subtilis*, which ferment straw, molasses and meal. Thanks to these technologies, the company has reduced the purchase of soybean meal by 22%, which has reduced total feed costs by 18% per year. At the same time, biocatalysis is widely used in the production of fermented premixes for ruminants. The National Centre for Biotechnology (n.d.) in Astana has developed enzyme complexes that promote the breakdown of fibre in feed, increasing the digestibility coefficient by 12-15%. This reduces concentrate consumption, lowers methane emissions from the rumen and improves feed conversion, which is important from both an environmental and economic point of view.

The reduction of the carbon footprint is a key aspect of sustainable agricultural production, especially considering that Kazakhstan's agriculture generates more than 15 million tonnes of CO_2 equivalents annually. Precision farming technologies play a significant role in this context. In 2023, as part of the Digital Villages of Kazakhstan programme, around 120 farms in the Pavlodar and Akmola regions gained access to Trimble GPS navigation and IoT sensors for measuring soil moisture and composition. This has reduced the use of mineral fertilisers by 20-25% and water consumption for irrigation by 30%, which in turn has contributed to a reduction in greenhouse gas emissions of 1.7 million tonnes of CO_2 equivalent per year (Digital Villages of..., 2020). Alternative energy sources, including biogas plants and solar panels, are also being actively introduced in the agricultural sector. For example, Farmers of Chilik (n.d.) in southern Kazakhstan use up to 40% of its electricity from biogas plants powered by cattle manure. This reduced diesel fuel consumption by 9.2 tonnes per year and CO_2 emissions by 110 tonnes. Solar panels installed on the roofs of farm buildings generate an additional 22-25 kW of energy per day, which fully covers the energy needs for cooling and lighting systems.

In Western Kazakhstan, especially in the Ural and Atyrau regions, organic farming based on the use of green manure, manure, compost and crop rotation is actively developing. According to the Ministry of Agriculture of the Republic of Kazakhstan (n.d.), the area of certified organic land increased from 35,000 ha in 2020 to 58,000 ha in 2024, while the overall carbon balance in these areas remains positive. The application of ESG principles in the agricultural sector is becoming increasingly popular as companies and farms realise that sustainable development contributes to competitiveness and long-term stability. Examples of ESG strategies implemented both in Kazakhstan and abroad demonstrate marked improvements in environmental sustainability, economic efficiency and social responsibility. These examples demonstrate how innovation and responsible business practices can transform the agricultural sector (Table 4).

***Table 4**. Successful cases of implementing ESG strategies in the agricultural sector*

Case	Technologies used	Increase in crop yields	Savings (percentage)	Reduction of CO_2 emissions	Reduced use of chemicals	Additional information
Kazakhstan: Olzha Agro Holding	Precision farming, minimal tillage	18%	12% on agricultural chemicals	-	20%	Reduced use of chemical fertilisers by 20%
Kazakhstan: EcoMilk LLP	Biodegradable packaging, solar panels	-	30% on energy costs	25%	-	500 solar panels on 20 farms
Germany BASF programme	Renewable energy sources, biogas plants	-	35-50% on electricity	40%	-	Processing of 50 thousand tonnes of agricultural waste per year
Netherlands: Van der Knaap vertical farming technology	Hydroponic and aeroponic systems for growing vegetables	20%	60% on pesticides	-	30%	Saves up to 95% of water, reduces chemical consumption by 30%

***Source:** compiled by the authors based on Olzha Agro (n.d.), EcoMilk (n.d.), BioEconomy Cluster (n.d.), L. Reiley (2023)*

An example of the implementation of ESG strategies in Kazakhstan is the agricultural holding Olzha Agro (n.d.), which in 2023 began using precision farming and minimum tillage systems. These innovations have significantly reduced the use of chemical fertilisers and pesticides, which has contributed to an 18% increase in yields. Thanks to the use of modern technologies, the agricultural holding saved 12% on agrochemicals, which not only reduced the environmental burden but also improved the company's financial performance. This approach contributes to the sustainable development of agriculture and reduces the negative impact on the environment, in line with ESG principles. Another successful example is EcoMilk (n.d.), an organic dairy producer that actively integrates sustainability principles into its operations. The use of biodegradable packaging and solar panels on its farms has significantly reduced the company's environmental footprint. Thanks to these measures, the company has reduced CO_2 emissions by 25% and cut energy costs by 30%. These steps not only contribute to environmental protection but also reduce operating costs, which increases the company's competitiveness in the market.

International experience also demonstrates the successful application of ESG strategies in the agricultural sector. In Germany, the Bioeconomy Strategy programme actively uses renewable energy sources and biogas plants to process agricultural waste. These innovations can significantly reduce energy costs by 35-50%. In addition, the use of such technologies leads to a 40% reduction in CO_2 emissions. This approach not only reduces the carbon footprint but also increases the energy independence of farmers, which contributes to their economic sustainability. A vivid example of the successful implementation of such technologies is the BioEconomy Cluster (n.d.). The Netherlands is a leader in the introduction of innovative technologies in agriculture, and vertical farming is one of the most prominent examples. Dutch farmers are actively using hydroponic and aeroponic systems to grow vegetables, which saves up to 95% of water, a critical resource in the context of climate change and water shortages. The use of vertical farms contributes to sustainable food production, reduces water and fertiliser costs, and enables indoor vegetable growth, minimising the need for pesticides and chemicals. An example of the successful implementation of such technologies is Van der Knaap (Reiley, 2023).

Examples from Kazakhstan, Germany and the Netherlands demonstrate how the implementation of ESG principles in the agricultural sector not only increases environmental sustainability but also improves economic efficiency. The use of innovative technologies such as precision farming systems, renewable energy sources and the development of organic agriculture ensures significant progress in reducing their carbon footprint, increasing yields and reducing operating costs. These examples are an important benchmark for other countries and companies seeking sustainable development and innovative solutions in the agricultural sector. The bioeconomy is a model of sustainable development based on the efficient and rational use of renewable biological resources. The agro-industrial complex offers many advantages, helping to balance the environmental, economic and social aspects of agriculture. The implementation of bioeconomic principles not only reduces the negative impact on nature, but also improves companies' financial results, creates jobs and develops rural areas. According to forecasts, by 2030, the value of the closed-loop bioeconomy could reach USD 7.7 trillion. At the same time, the World Bioeconomy Forum estimates the value of the global bioeconomy at USD 4 trillion, with a forecast of growth to USD 30 trillion or more by 2050 (Cano-Gómez *et al.,* 2024).

One of the important aspects of the bioeconomy in Kazakhstan's agro-industrial sector is achieving environmental sustainability by reducing the chemical load on soil, water bodies and the atmosphere. For instance, using biological products based on *Trichoderma viride* and *Bacillus subtilis* on farms in the Akmola region helped cut down on fungicide use by 30%, which led to a 45% drop in wheat disease compared to control plots. At the same time, the use of biodegradable organo-mineral fertilisers produced from sapropel and chicken manure on farms in the Karaganda region has reduced nitrate content in the soil by 17% and improved the phytosanitary condition of rapeseed crops (Yerpasheva *et al.,* 2022).

From a social perspective, the bioeconomy is substantial in the development of rural areas and the creation of new jobs. In 2023, 260 new jobs were created in the fields of bioengineering, compost production and organic fertilisers as part of the state programme "Жасыл ауыл". A biogas plant using livestock manure began operating in the Talas district, providing energy for 14 greenhouse farms and creating more than 40 jobs. At the same time, the development of organic farming has encouraged young people to return to rural areas, and in 2022-2024, 18% of agronomy graduates started small farms using bioeconomic practices (Under the "Green…, 2019). Thus, bioeconomy in the agricultural sector of Kazakhstan emphasises the relationship between environmental sustainability, economic benefits and social integration of rural residents. Its implementation contributes to the creation of an adaptive and efficient model of agricultural production that not only reduces the burden on natural ecosystems but also stimulates economic growth in the regions, improving the quality of life in rural areas.

DISCUSSION

Bioeconomy, as a key area of sustainable development in the agricultural sector, has become increasingly important. The study demonstrated that ESG principles focusing on environmental, social and governance sustainability significantly affect the development of the agricultural sector. Environmental practices, such as reducing carbon footprint and rational use of natural resources, improving the ecological situation and reducing environmental impact. Social initiatives, including improving working conditions and creating new jobs, are becoming the basis for social progress and improving the quality of life of rural residents. In addition, the introduction of transparent management approaches improves trust between producers and consumers, which has a positive impact on the economic situation in the industry. This issue was also studied by B. Wang *et al.* (2024), whose results confirmed that ESG strategies play a key role in the development of the agro-industrial complex. They reduce the negative impact on the environment by introducing energy-efficient technologies and reducing greenhouse gas emissions. In addition, ESG-oriented companies have more opportunities to attract investment and receive government subsidies.

P. Vrabcová and H. Urbancová (2023) also demonstrated that sustainable business practices in agriculture include the rational use of natural resources and the use of precision farming technologies. The social component of ESG aims to improve the working conditions of farmers and support local communities. Effective ESG management increases the transparency of supply chains and reduces the risks associated with climate change. Notably, the implementation of ESG strategies in the agricultural sector requires significant investments and reworking of business models, which can be difficult for small and medium-sized agricultural enterprises (Hopka & Kovtun, 2024). However, in the long run, such changes contribute to the sustainability of agriculture by reducing dependence on climate risks and fluctuations in resource prices. Furthermore, consumers and investors increasingly prefer companies that adhere to the principles of sustainable development, making the ESG approach not only ethically justified but also economically beneficial.

The rational use of biological resources has become a key factor in ensuring sustainability and increasing crop yields (Khrystenko *et al.*, 2025). The study analysed new agricultural technologies, such as the use of biodegradable fertilisers and biopreparations, which contribute to improving plant resilience and protecting them from disease. These innovative methods, including environmentally friendly fertilisers, reduce the negative impact on the environment while increasing agricultural efficiency. Such practices are fully consistent with the principles of sustainable development, providing long-term environmental and economic benefits. D. Wang *et al.* (2023) concluded that the efficient use of bioresources in agriculture is aimed at preserving ecosystems and increasing productivity without depleting natural resources. This includes crop rotation, organic farming and the use of biological plant protection methods. These approaches help restore soil fertility and reduce the negative environmental impact of the agricultural sector.

E. Duncan *et al.* (2021) determined that innovative agricultural technologies, including precision farming, biotechnology and automation, contribute to more efficient use of resources. Drones and sensors can be used to monitor the condition of crops and optimise irrigation and fertiliser management. The introduction of digital solutions reduced costs, increased yields and improved the resilience of agriculture to climate change. The findings confirm the results of previous studies, showing that innovative agricultural technologies do indeed contribute to more efficient use of biological resources. Precision farming and biological plant protection methods help minimise losses and reduce environmental impact. As a result, agricultural enterprises not only gain economic benefits but also achieve long-term environmental sustainability, which correlates with the principles of rational use of natural resources.

The circular economy and zero-waste production have become key trends in the agricultural sector (Ciuła *et al.*, 2024). Recycling of agricultural waste, such as biogas, composting and feed additives, contributes to the efficient use of resources, reducing waste and the negative impact on the environment. The use of agricultural by-products in the production of biofuels and biopolymers also reduces dependence on fossil energy sources and promotes the development of environmentally friendly technologies (Shumka *et al.*, 2021). Such approaches not only increase economic efficiency but also significantly strengthen the environmental sustainability of agribusiness. The study by L. Rojas *et al.* (2022), emphasising that the circular economy in the agro-industrial complex prioritises minimisation of waste and maximising the use of by-products, is noteworthy. In agriculture, this is manifested in the processing of organic waste into biochar, biogas or compost, which helps to reduce the environmental impact. This approach not only helps farmers reduce costs but also contributes to the creation of closed production cycles, increasing the sustainability of the agricultural sector.

A. Taghizadeh-Alisaraei *et al.* (2023) concluded that zero-waste production in agriculture is based on the full use of resources and the recycling of by-products. For instance, straw is used to produce feed, fertiliser or biofuel, and food waste is processed into feed or organic fertiliser. The introduction of such technologies reduces the negative impact on the environment and increases the profitability of agricultural production. These results confirm the conclusions outlined in the previous section, as the circular economy and zero waste production not only reduce resource waste but also increase the efficiency of the agricultural sector. Examples of successful use of by-products show that closed production cycles can reduce costs and improve the environmental sustainability of agriculture (Shebanin *et al.*, 2024). Thus, the introduction of circular economy principles in the agricultural sector is a key factor for increasing the competitiveness and sustainable development of the industry.

The use of biotechnology, such as genetic engineering and biofermentation, has proven to be a crucial factor in increasing the resilience of crops to various stresses, including drought and disease. Studies have shown that the introduction of new plant varieties adapted to adverse conditions, as well as the development of new types of feed, fertilisers and food additives using biocatalysis, improves production results and contributes to the sustainability of the agricultural sector. These biotechnological innovations have significantly increased both agricultural efficiency and food security. A. Tyczewska *et al.* (2023) confirmed that biotechnology in the agricultural sector contributes to increased yields, improved plant resistance to stressful conditions and reduced need for chemical fertilisers. Modern methods, such as biofermentation and the use of beneficial microorganisms, help to improve soil conditions and protect crops from diseases. These technologies not only increase agricultural productivity but also contribute to its environmental sustainability.

R. Govindasamy *et al.* (2022) also concluded that genetic engineering and biofermentation are key in creating new plant varieties with improved characteristics, as well as in developing more efficient methods of biomass processing. Genetic modification makes it possible to create crops that are resistant to drought, pests and diseases, which helps to reduce crop losses. Biofermentation, in turn, is used to produce biofertilisers, biofuels and fermented feed, which contributes to more efficient use of resources in agriculture. Comparing the data obtained during the research, it can be noted that biotechnology is an important factor in improving the efficiency and sustainability of the agricultural sector. Genetic engineering and biofermentation not only improve the characteristics of crops but also help reduce the use of chemical fertilisers and pesticides. This improves productivity while reducing the environmental footprint.

Reduction of the carbon footprint has become a key aspect of the sustainable development of the agricultural sector. The introduction of precision farming technologies, including the use of drones, IoT and Big Data, has significantly reduced the consumption of resources such as water, fertilisers and energy. This has not only reduced carbon emissions but also increased economic efficiency by cutting costs. The development of organic farming and the use of alternative energy sources, such as solar panels and biogas plants, have become additional measures to reduce carbon emissions and mitigate climate impact. J. Rajakal *et al.* (2021) concluded that reducing the carbon footprint in the agricultural sector is achieved by optimising production processes, using renewable energy sources and reducing greenhouse gas emissions. The introduction of precision farming technologies, the use of biological fertilisers and energy-saving equipment helps to reduce the negative impact on the environment. In addition, carbon farming practices, such as green manure and minimum tillage, improve CO_2 sequestration.

U. Bhatti *et al.* (2024) noted that the greening of agriculture is aimed at creating a balance between agro-industrial processes and natural ecosystems. This includes the use of organic fertilisers, the reduction of chemicals and the introduction of conservation technologies. Such approaches not only preserve biodiversity but also increase the resilience of the agricultural sector to climate change. The analysis of the study results demonstrated that the reduction of the carbon footprint and greening agriculture are important components of the sustainable development of the agro-industrial complex. The introduction of environmentally friendly technologies and the use of alternative energy sources leads to a significant reduction in greenhouse gas emissions and improved soil conditions (Parkhomets *et al.*, 2023). Thus, the transition to more environmentally friendly agricultural practices not only reduces the negative impact on the environment but also contributes to improving the economic efficiency of the agricultural sector.

The benefits of the bioeconomy for the agricultural sector include improved environmental sustainability, increased economic efficiency and social relevance. Environmental benefits, such as reduced soil, water and air pollution, contribute to improving the environment and preserving natural resources. Economic efficiency is achieved by reducing the cost of raw materials and energy resources, which strengthens the competitiveness of enterprises. The social significance of the bioeconomy is manifested in the creation of new jobs and the improvement of the lives of rural residents, which is a key element of sustainable development and social stabilisation. All these factors underline the role of the bioeconomy as a strategic direction for the long-term sustainable development of the agro-industrial complex.

CONCLUSIONS

The results of the study demonstrated that the bioeconomy is an important aspect of the sustainable development of the agricultural sector. Implementation of ESG strategies in the agricultural sector helps to reduce the carbon footprint, efficiently use natural resources and improve the social responsibility of business. By following ESG principles, companies gain competitive advantages, strengthen investor and consumer confidence, and increase their economic sustainability. The rational use of biological resources contributes to increased agricultural productivity while reducing environmental impact. The use of biodegradable fertilisers and biopreparations improves soil quality and reduces water and air pollution. The circular economy and waste-free technologies for processing agricultural waste create added value, including biogas, biofuels and organic fertilisers. The use of biotechnology, such as genetic engineering and biofermentation, contributes to the creation of plant varieties that are resistant to stress factors and to the development of innovative feeds and fertilisers. These technologies increase yields, reduce the need for chemicals and reduce the cost of agrochemicals. The use of precision farming, drones and IoT technologies helps to use resources efficiently, and the transition to renewable energy sources reduces the environmental impact of agriculture on the climate.

In Kazakhstan, the area of agricultural land designated for sustainable farming increased from 43 million hectares to 47 million hectares, and the use of organic fertilisers increased from 5% to 7%. The area covered by drip irrigation increased from 1.5 million hectares to 3 million hectares. Food losses decreased from 16% to 13%. The share of recycled waste in agricultural production increased from 22% to 30%, and the volume of recycled organic waste increased from 1 to 2 million tonnes. In the biotechnology sector, the share of genetically modified crops increased from 5% to 9%, and the carbon footprint decreased by 5 million tonnes of CO_2. Examples from Kazakhstan, Germany and the Netherlands show that the bioeconomy increases the efficiency of agriculture and reduces its environmental footprint. Olzha Agro reduced chemical use and increased yields by 18%, while EcoMilk reduced CO_2 emissions by 25%. In Germany, biogas plants have reduced energy costs by 50%, and in the Netherlands, vertical farms have reduced water consumption by 95%. These technologies make the agricultural sector sustainable and competitive. The long-term impacts of biotechnology on agroecosystems and socio-economic development in rural areas are not well understood, which is a limitation of this study. To determine the economic efficiency of bioeconomic technologies, additional research is required in different climatic and geographical conditions.

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CONFLICT OF INTEREST

None.

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Біоекономіка як стратегічний напрям сталого розвитку агропромислового комплексу

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Анотація. Дослідження спрямоване на виявлення ключових принципів біоекономіки та їхнього впливу на екологічну, економічну та соціальну стійкість агропромислового комплексу. Під час дослідження було проведено комплексний аналіз наявних практик застосування Environmental, Social, Governance (ESG)-стратегій і біоекономіки в агропромисловому комплексі, включно з вивченням успішних кейсів і порівняльним аналізом ефективності впровадження інноваційних технологій. Під час проведеного дослідження було встановлено, що впровадження принципів біоекономіки в агропромисловий комплекс істотно сприяє зміцненню стійкості та підвищенню ефективності сільськогосподарського сектору. У період з 2021 по 2024 рік спостерігалося зростання площ, що використовуються для сталого землеробства – з 43 до 47 млн гектарів, а також збільшення частки органічних добрив у загальному обсязі – з 5 % до 7%. Використання крапельного зрошення також зросло – з 1,5 до 3 млн гектарів. Паралельно з цим відбулося зниження продовольчих втрат в агросекторі з 16 % до 13 %, а ефективність використання водних ресурсів збільшилася з 3,5 до 4 км^3. Розвиток циркулярних технологій приніс помітні результати: частка перероблених відходів в агровиробництві зросла з 22 % до 30 %, а кількість підприємств, що застосовують такі рішення, збільшилася з 90 до 150. Застосування біотехнологій також справило позитивний вплив – частка ГМ-культур зросла з 5 % до 9 %, а вуглецевий слід було скорочено з 5 до 3 млн тонн CO_2. Вивчення успішного впровадження ESG-підходів в агробізнесі, зокрема в Казахстані, Німеччині та Нідерландах, засвідчило зниження застосування хімічних добрив, поліпшення якості продукції та зменшення викидів парникових газів. Наприклад, агрохолдинг «Олжа Агро» знизив використання агрохімікатів на 12%, домігшись при цьому зростання врожайності на 18 %. А компанія «EcoMilk» завдяки використанню біорозкладного пакування та встановленню сонячних панелей скоротила викиди CO_2 на 25 %. Загалом, результати аналізу підтвердили значущість інтеграції біоекономічних та ESG-принципів для сталого розвитку агропромислового комплексу та підвищення його соціальної значущості

Ключові слова: екологічний слід; точне землеробство; циркулярна економіка; біоферментація; ESG-стратегії