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Circular Economy, Environmental, Economic and Social Effects in Agriculture

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ABSTRACT

In modern conditions, the priority area for the agro-industrial complex is the introduction of resource-saving and environmentally friendly models of enterprise operation, which is especially important in the regions of Northern Kazakhstan . aspect more appropriate conditioned climatic risks and availability natural resources northern territories , as well as presence big quantities waste and their ineffective using . The present study directed on studying mechanisms , models development circular economics in rural areas economy of Kazakhstan, considering economic , social and environmental effects . The main objective of the study is to develop a methodology for implementing the principle of circular economy and education. be based on materials from agricultural enterprises in northern Kazakhstan. Methodology . Methodological research include. How both quantitative and qualitative methods on level enterprises . study interactions farms with a chain creation cost respectively meso-level and study influences regional stability on macro level . indicators from the position stability development rural territories , the Triple Bottom Line concept , which allows measure aggregate effects implementation circular principles activities agricultural enterprises developed author's methodology By effective implementation equipment , optimizing temporal lag on development and adaptation this equipment in the activities of enterprises . Proposed system key indicators For assessments sustainable development agricultural enterprises on basis implementation tools circular economy. Results . Established decrease volumes waste , provision increases employment , population , increase profitability and formation new sources income For fortifications social stability rural territories . In general By rural farm is demonstrated high level adaptations agricultural enterprises to circular mechanisms , principles and practices . this celebrated limitation access to finance , knowledge technologies with sides small farms rural economy. implementation. Uniqueness enterprises allowed reduce cycles implementation, on the contrary, is effective is used in reality enterprises. In conclusion research developed recommendations By formation national politicians circular economics in rural areas farm, which directed on effective distribution resources, development ecosystems, sustainable development agro-industrial complex and stimulation innovations.

Keywords: Agriculture, Circular economy, Waste, Economic efficiency, Environmental effects, Resource conservation, Social sustainability, Sustainable development.

INTRODUCTION

Modern agriculture in Kazakhstan is undergoing a systemic transformation driven by the need to transition from extensive growth to sustainable development. Increasing climate risks, land degradation, and high energy intensity in production are driving the need for a transition to a circular economy model focused on the rational use of natural resources, waste minimization, and the integration of environmentally friendly technologies.

The implementation of a circular model in agriculture consists of building closed-loop production and economic systems, where resources, materials, and waste are maximally recycled, and the final product creates added value at every stage of the life cycle.

The aim of this study is to assess the economic, environmental and social effects of introducing circular economy principles in agriculture in Kazakhstan, followed by the development of scientifically based recommendations for the development of remanufacturing and sustainable production chains.

Climate challenges—drought, freshwater shortages, and rising average annual temperatures—combined with low levels of agricultural processing pose a threat to food security. According to the Bureau of National Statistics of the Republic of Kazakhstan, only about 25% of agricultural products are processed, which is significantly lower than the European average (55–65%).

To address these issues, it would be helpful to adapt international experience. Germany has demonstrated the effectiveness of its circular economy legislation (KrWG, VerpackG, and BattG laws), Uzbekistan has successfully implemented agro-clusters and digital vouchers, and Russia has developed regional digital organic waste management platforms. Kazakhstan, with its significant agricultural potential and annual organic waste generation of over 1.4 million tons, could integrate these approaches into its own national circular agriculture model. This approach would reduce dependence on raw materials, increase the competitiveness of the agricultural sector, and facilitate the transition to sustainable methods for using agricultural producers' limited resources

A review of the scientific literature reveals a significant diversity of approaches to understanding the concept of the circular economy (CE). According to Kirchherr et al. [1], there are over 120 different definitions of this term, reflecting its interdisciplinary nature and close connection with the concepts of sustainable development, the green economy, and Industry 4.0.

Research by Yuan, Bi, and Moriguchi [2] laid the foundation for integrating principles of industrial ecology, bionics, and systems engineering, forming a unified theoretical framework for a circular economy. Their model formed the basis for strategies in China and Japan aimed at creating a closed-loop society and reducing dependence on primary resources.

It's important to study international experience in implementing a circular economy across various sectors. India is demonstrating positive results. The development of low-waste manufacturing. Thank you. It has dynamically transitioned from a linear model to a circular economy approach, due to the lack and scarcity of resources, as well as environmental protection measures. For example, the waste management rate has increased from 18% in 2014 to 75% in 2023. Forgiveness, reuse, recycling, and bio-waste are all part of this [3]

This concept is being implemented in urban and rural areas of India for solid waste and e-waste management. This is, in turn, within the framework of renewable energy. This will undoubtedly lead to financial benefits, the creation of new jobs, and a reduction in environmental emissions [4]. It is important to note, however, that there is poor coordination between government agencies and authorities in implementing circular economy principles in a number of countries.

Importantly, the principles of a circular economy are similar to those implemented in other economic sectors, such as construction [5] Natural waste accounts for up to 40% of the country's total waste, including 36% from the energy sector. This accounts for over 35% of greenhouse gases [6]. The environmental, economic, and social aspects of implementing circular economy principles are applicable to all sectors of the real economy. This includes the development of biofuel projects, which reduce agricultural waste and increase the potential of energy resources for agriculture. Implementing these principles in agriculture is a strategic issue, as this sector ensures food security and public health [7].

There are four strategies for implementing a circular economy in the agro-industrial sector. These include reducing resource cycles, slowing them down, closing them, and restoring resource flows [8]. This strategy revolves around principles such as reduction, reuse, modernization, repurposing, recycling, and restoration. This strategy, which implements the principles of reducing the circular cycle, entails reducing the intensity of agricultural resource use. This, in turn, will reduce environmental impacts, thereby implementing the principle of reducing cycles [9]. Reducing the cycles entails maximizing the value of natural resources and agricultural products. It is also important to implement the principles of reuse and modernization of resources used in the agro-industrial complex and MTB, including extending the service life of agricultural products, reducing and preventing food waste, and creating conditions for better preservation of agricultural products) [10]. The third circular economy strategy is based on the principles of reuse and recycling of materials extracted from the composition and value chain. This strategy enables the creation of new value through recycling and reuse, as well as energy production. The fourth strategy focuses on measures aimed at reducing and improving the use of natural resources through the implementation of regenerative principles. This includes the implementation of regenerative agriculture projects, soil health measures, and biodiversity enhancement, all aimed at improving air quality. It is important to note that these strategies and principles are not mutually exclusive, although they are complementary and are applied in stages [11]. It should be noted that when studying circular economy mechanisms in agriculture, the stages of the agricultural production cycle are distinguished for managing the relevant resources, including the management or organization of management projects for seed stock, the use of fertilizers, pesticides, energy, fuel, water, and material and technical resources, including land preparation, namely, tillage, sowing, and transplanting. Further processes include increasing yields, the quality of reproduction, and agricultural production through the use of fertilizers, pest control, harvesting, mulching, and pruning [12]. As well as the management of agricultural production in plant cultivation, which generates by-products and waste, a certain methodological gap can be identified in the research that demonstrates the socioeconomic and environmental impact of the circular economy. Several publications, however, focus on barriers and measures aimed at developing a circular economy) [13]. Barriers to the implementation of a circular economy include the necessary regulatory documentation, numerous regulatory restrictions, and government guarantees aimed at implementing agricultural projects. Given high costs and a lack of knowledge for their application, low levels of informational implementation by producers and consumers, and a deficient reverse logistics chain, a methodological gap exists in implementation in agricultural cooperation, making the circular economy an important element in overcoming the aforementioned barriers [14].

The European school of thought views the circular economy as a tool for environmental regulation and innovative business. It facilitates a transition from the linear "take-produce-dispose" model to the "reduce-reuse-recycle" model [15, 16]. In agriculture, these principles are manifested through the formation of value chains, the minimization of organic and industrial waste, the reuse of resources, increased energy efficiency, and the implementation of remanufacturing practices, where products or equipment are restored and modernized for reuse [17].

The development of circular models is creating a so-called "spiral economy," where each stage of a product's life cycle becomes a source of data, raw materials, and energy for subsequent stages [18]. The environmental impact is manifested in reduced greenhouse gas emissions, reduced use of primary resources, reduced soil and water pollution, and the preservation of biodiversity and increased ecosystem resilience in agriculture. This model helps achieve environmental sustainability, reducing the burden on soil and water resources, while simultaneously increasing the long-term economic efficiency of agricultural production [19].

In terms of economic impact, the implementation of circular economy principles in the agricultural sector helps reduce raw material and energy costs, stimulates innovative business models, and creates new opportunities for local jobs [20].

The social aspect manifests itself in improved quality of life in rural areas, increased food security, and stronger local connections between producers and consumers. However, the successful implementation of a circular economy requires not only technological innovation but also institutional changes: the development of legislation, waste recycling infrastructure, and digital monitoring systems for raw material and energy flows [21-22].

Thus, the circular economy in agriculture is viewed as a comprehensive sustainable development strategy integrating environmental, economic, and social aspects. In the context of Kazakhstan, the implementation of CE principles is particularly important given the country's high potential in the agricultural sector, limited water and soil resources, and the need to improve food security. Research prospects in Kazakhstan include the development of adapted closed-loop production models, assessment of the environmental impacts of reducing waste and emissions, the implementation of remanufacturing and resource recycling, and the study of economic and social benefits for local communities. Such research can contribute to the development of an effective sustainable agricultural development strategy, reducing the burden on natural resources, and the creation of innovative business models focused on the long-term sustainability of Kazakhstan's agricultural enterprises [23-25].

The primary objective of the study was to assess the economic, environmental, and social impacts of the project to implement circular economy principles in agriculture in the Republic of Kazakhstan, followed by the development of scientifically sound recommendations aimed at fostering sustainable production chains. In accordance with this objective, the following tasks were identified: Assess the current state of Kazakhstan's agriculture from a sustainability and circularity perspective; and analyze the economic challenges facing agriculture [26]. This is a highly relevant and practical example of implementing circular economy principles in the agro-industrial complex. It also assesses the effectiveness of these principles, applicable to specific enterprises, analyzes how to interact and exchange resources between agro-industrial enterprises within the framework of organizing sustainable closed-loop value chains, evaluates the circular economy, and assesses its socio-environmental impact on the development and formation of sustainable production chains in agriculture. It is important to highlight the scientific significance of the presented study, which includes the following. A comprehensive assessment of the economic, environmental, and social impacts of implementing structural economic principles in the agro-industrial complex provides a comprehensive understanding of the agro-industrial complex's capabilities for economic development. This study explores the specific benefits and identifies and understands the challenges of transitioning to a circular economy. Based on a study of international experience, an analysis is conducted and a specific tool for adapting the implementation of circular economy principles in agriculture is developed for the Republic of Kazakhstan. A new methodological approach to assessing the effectiveness of circular economy principles at the enterprise level in the region is proposed. Furthermore, this presentation has practical significance. This article may be presented to government agencies involved in developing strategies and policies aimed at developing circular economies in agriculture, including the Ministry of Agriculture of the Republic of Kazakhstan and the Ministry of Economy of the Republic of Kazakhstan. The presented research may be applicable to the activities of agricultural enterprises implementing a circular economy to ensure their competitiveness.

MATERIALS AND METHODS

The methodological approach of the study is based on a comprehensive assessment of the environmental, social and economic effects of the implementation of circular economy principles in agriculture and a combination of quantitative, qualitative and analytical methods, which made it possible to obtain reliable and representative results for agricultural enterprises in the Northern region of Kazakhstan.

An analysis of the implementation of circular practices was conducted considering the multi-level impact on agricultural enterprises and the region as a whole. At the individual farm level, the effectiveness of the circular economy was assessed, including the optimization of side streams, the digitalization of logistics processes, and increased profitability. Simultaneously, interactions and resource exchanges between agricultural enterprises were examined, such as the joint use of biogas plants, waste recycling, and cooperation on secondary products, which contributed to the formation of sustainable closed-loop value chains. At a broader, regional level, the impact of the circular economy on social and environmental indicators was analyzed: employment generation, development of social capital, and improved environmental safety and sustainability of the agro-industrial complex.

This comprehensive approach made it possible to trace the synergistic effect of circular practices at the micro, meso, and macro levels simultaneously.

The research was conducted using data from the Department of National Statistics of the Republic of Tatarstan, including information on the production, processing, and disposal of agricultural products in the country. Open publications from the Scopus international database were used to study international experience in implementing church principles on a canning farm. Data from agricultural enterprises in the northern region of Kazakhstan were used to test the circular economy implementation model. In order to present the results and effectiveness of applying the developed circular economy principles to specific enterprises, the following methods were used. In this case, an integrated assessment methodology was used to conduct quantitative analytical and qualitative methods for assessing the environmental, social, and economic effects of implementing circular economy principles in agriculture.

LCA analysis made it possible to quantify the environmental footprint of products at all stages of the life cycle – from the cultivation of raw materials to processing and waste disposal.

The ESG analysis assessed the sustainable management of enterprises across three components: environmental, social, and governance. Agricultural enterprises with high ESG ratings demonstrated economic sustainability, social trust, and effective implementation of innovative practices.

The SROI methodology was used to quantify social impacts, including job creation, staff development, and investments in social initiatives.

The Triple Bottom Line (TBL) model allowed for the integration of economic, environmental and social indicators into a single assessment system.

Thus, the integrated application of LCA, ESG, SROI and TBL provides a comprehensive assessment of the synergistic effects of the circular economy, confirming its economic, environmental and social effectiveness at the micro, meso and macro levels.

The implementation of circular economy (CE) principles in the agriculture of Northern Kazakhstan is aimed at creating closed production cycles, actively using the waste of one production process as raw material for another, and developing processing and remanufacturing processes, including biogas and compost production, as well as converting organic and agricultural waste into new products and fertilizers. Particular attention is given to optimizing water use and improving the processing of agricultural products and waste, contributing to sustainable and resource-efficient development of the region's agro-industrial complex.

The implementation of circular economy principles requires the involvement of the state, business, science, and rural communities. Government bodies provide the legal and institutional framework, offering tax incentives, subsidies, and grants for sustainable production.

Agricultural enterprises and farms implement practical solutions for processing, utilizing by-products, and increasing resource efficiency.

Scientific and educational institutions develop technologies and train specialists.

Financial institutions, including international partner programs (FAO, UNDP, GEF), support the transition to circular models through targeted loans and investment programs.

Agricultural enterprises are the main "players" in implementing CE principles, ensuring continuity in recycling and remanufacturing cycles in agriculture.

In the milling industry, grain processing by-products-bran and dust-can be used to produce feed, organic fertilizers, and biofuel. Grain cleaning waste is processed into feed additives and biogas. Implementing closed-loop water systems and biodegradable packaging reduces the environmental impact of enterprises.

In the dairy processing sector, whey processing is particularly relevant. In a circular model, whey is used to produce protein concentrates, beverages, or feed ingredients. Using by-product streams allows product diversification, cost reduction, and increased environmental efficiency. Energy optimization through heat recovery, water reuse, and biogas technologies creates conditions for zero-waste production.

In the grain processing sector, waste-such as husks, pulp, and other by-products-can be processed into organic fertilizers, biogas, and biopolymers. Biotechnological solutions enable the production of bioplastics and feed proteins, forming new economic segments. Meanwhile, the introduction of digitalization and energy-efficient milling complexes increases productivity and reduces energy consumption.

Mixed farms integrate biological cycles of crop and livestock production. Manure and plant residues are used to produce biogas and organic fertilizers, which are returned to the soil. This "crop-livestock-energy-fertilizer" system increases productivity and reduces dependence on mineral fertilizers. Precision farming technologies optimize the application of organic inputs and maintain soil fertility.

The implementation of circular economy requires a comprehensive approach, including:

- Improving the regulatory framework and developing a national circular agriculture strategy with a certification system;
- Creating innovative technological infrastructure, demonstration farms, and biomass processing laboratories;
- Implementing financial support mechanisms—"green" loans, subsidies, and international grants;
- Developing educational programs on resource efficiency, biotechnology, and digital process monitoring;
- Promoting cross-sectoral cooperation, where waste from one production process is used as raw material for another.

Scientific and technological principles of circular economy formation are based on the integration of biotechnology, energy-efficient, and digital solutions. The biotechnological component involves processing crop and livestock waste into biogas and organic fertilizers, as well as using by-products of grain and milk processing (bran, husks, whey) for protein concentrates, feed, and biopolymer production.

Energy optimization is achieved through heat recovery systems, closed-loop water cycles, and the use of renewable energy sources such as biogas, solar, and wind power. This allows enterprises to reduce energy consumption by 20–30% and increase autonomy.

Digitalization and automation enhance production process management accuracy. The use of IoT, precision agriculture sensors, and geographic information systems (GIS) enables monitoring of water, fertilizer, and energy use, optimization of biomass logistics, and creation of digital platforms for resource exchange between enterprises. The development of biodegradable packaging from agricultural waste further reduces plastic waste.

To assess the effectiveness of CE implementation, a scientific and technical monitoring system integrated with databases on resource flows, energy efficiency, and environmental characteristics of enterprises is applied. Artificial intelligence and machine learning methods allow forecasting waste and secondary resource volumes, optimizing production processes, and improving the manageability of agricultural systems. Monitoring is complemented by digital twins of enterprises, enabling scenario modeling and evaluation of new technologies' impact on sustainability and the economy of agricultural production.

Expected results of CE implementation in Northern Kazakhstan's agriculture include:

- Increasing the utilization of agricultural waste to 70–80%;
- Reducing energy consumption by 20–30%;
- Cutting greenhouse gas emissions by up to 40%;
- Creating new biotechnological clusters and jobs in the "green" technology sector;
- Enhancing regional investment attractiveness, product competitiveness, and ensuring food and energy security.

Circular economy in Northern Kazakhstan's agriculture represents an innovative model of sustainable development based on rational use of natural resources and integration of science, technology, and management. Its implementation requires a comprehensive approach, uniting the efforts of the government, business, research institutions, and rural communities.

The creation of a regional circular agrotechnology platform and the implementation of digital monitoring tools will facilitate the transition to zero-waste production, reduce environmental impact, and enhance the sustainability of rural areas. In the long term, the circular economy may become the foundation of a new paradigm in agricultural production, combining environmental responsibility, economic efficiency, and technological innovation [28-34].

Methodology. The combination of digitalization and waste recycling technologies creates a balanced circular agriculture model for the Northern Region of Kazakhstan, focused on economic efficiency, social impact, and environmental sustainability.

The method for calculating the predicted values is based on the proportional relationship between the level of implementation p (%) and the maximum possible effect E max :

$E(p)=E_{\max}\times\frac{P}{100}$ P/100) (1)

where: E(p) is the expected effect of the indicator at the implementation level p;

E max - maximum effect at 100% implementation;

p - share of implementation of practices (%).

The maximum values of E max $_x$ are pre-determined by back-calculation based on the 60% extended deployment scenario.

To forecast the life cycle of innovation and optimize the innovative activities of agricultural enterprises, an improved methodology for forming an innovation cycle is proposed using digital technologies, economic and logical analysis, and mathematical modeling.

To forecast the technological cycle of agricultural processing and optimize the innovative activities of agricultural enterprises, an improved methodology for forming an innovation cycle is proposed using automated control systems of digital technologies, economic and logical analysis, and mathematical modeling.

1. Analytical stage: analysis of the dynamics of innovative development. Data on similar automated processing systems is collected and processed (based on performance, reliability, service life, maintenance costs, and energy efficiency).

Based on the time series Y(t), an innovative product life cycle curve is formed, approximated by a logistic function:

$$\mathrm{Y}(t)=\frac{\mathrm{Ymax}}{1=\mathrm{e}^{-\mathrm{k(t+t0)}}}(2),$$

where Ymax - the maximum level of technological development,

k - the coefficient of innovation intensity,

t_0 - the moment of transition to the stage of technology maturity.

The rate of change of innovation potential is determined:

$$\frac{dY}{dt}-kY\ 1-\frac{Y}{Ymax}(3),$$

This indicator allows us to quantitatively assess the rate of technological innovation and modernization.

2. Forecasting stage: analysis of development factors. Expert analytical modeling of long-term trends is conducted:

- Scientific and technological progress in the field of automation of technological processes and energy efficiency;
- Changes in market demand for equipment and the needs of mining enterprises;
- Influence of environmental and social factors.
- To assess the mutual influence of factors, a multiple dependence regression model is used:

$$Y=\beta_0+\beta_1X_1+\beta_{2\beta_1X_1}X_2\ldots+\beta_nX_n+\varepsilon \quad (4)$$

where Xi are the key determinants of innovative development (R&D, investments, production costs, market demand, etc.),

βi - elasticity coefficients,

ε is a random component.

3. Digital modeling and prediction curve construction. Digital platforms and artificial intelligence technologies (machine learning, simulation modeling) are used to refine the life cycle curve parameters.

Based on a comparison of the results of the analysis and forecasts, a predictive innovation curve for a new product is formed:

$$Yp(t) = f(Y_{\text{equivalent}}(t), X(t), \beta_i(5)$$

where f - function obtained using digital optimization tools (eg neural network regression analysis or genetic algorithms).

4. Innovation Cycle Optimization Stage. Optimization of the duration of innovation cycle stages (R&D, implementation, growth, maturity, substitution) is achieved by minimizing total costs while maintaining maximum innovation output:

$$\min_t C = (C_i^{R\&D} + C_i^{Operation} - P_i^{operating\ profit})(6)$$, under restrictions:

Thus, the methodology allows us to assess the comprehensive impact of waste-free technologies on production processes and the economic performance of agricultural enterprises, as well as to develop practical recommendations for their implementation, taking into account environmental, social, and economic effects.

Scientifically sound agricultural production methods and the integration of digital technologies contribute to improved product quality, optimized production processes, and reduced operating costs. The use of automated process control systems ensures the efficient operation of enterprises in various natural and climatic conditions and supports the sustainable development of the agro-industrial complex. Innovation and technological modernization remain key factors in enhancing the industry's competitiveness.

RESULTS

Unlike most economic sectors, agricultural activity is characterized by significant unevenness due to seasonal factors. This specificity creates imbalances in the production cycle, complicates product life cycle assessments, and leads to uneven income distribution within the reporting period.

A comprehensive assessment of the performance of Kazakhstan's agro-industrial complex for 2020–2023, based on key indicators, allows us to identify key development trends and determine factors influencing its effectiveness (Table 1).

Table 1 . Key indicators of agriculture in Kazakhstan for 2020–2023*

Indicator	2020	2021	2022	2023
Employment in agriculture (%)	13 , 2	12 , 8	12.5	12 , 13
Gross output (billion tenge)	6,890	7 110	7,420	7,625.2
Grain production (million tons)	17 , 5	19 , 2	18 , 6	18 , 9
Volume of agricultural waste (straw) (million tons)	2 , 2	2 , 3	2 , 4	2 , 5
Greenhouse gas emissions (agriculture sector) (million t CO_2 -eq.)	36	35	33	33
Number of farms (thousand)	380	390	395	400
Average income per farm (thousand tenge)	4 100	4,350	4,600	4,750

Note: *Bureau of National Statistics of the Republic of Kazakhstan

An analysis of the presented data in the context of the environmental, social, and economic effects of the circular allows us to draw a number of conclusions about the trends in the transformation of Kazakhstan's agro-industrial complex in 2020–2023.

From an economic perspective, increasing gross output while reducing labor costs demonstrates increased resource efficiency. This reflects one of the key principles of the circular economy: achieving economic growth through rationalization and closed-loop material flows, rather than simply expanding resource consumption.

From an environmental perspective, the observed reduction in greenhouse gas emissions from 36 to 33 million tons of CO_2-eq and the gradual increase in the volume of recycled agricultural waste (from 2.2 to 2.5 million tons) reflect positive changes toward increasing the industry's environmental sustainability. This indicates the emergence of preconditions for the implementation of circular practices—such as the use of biomass and agricultural waste for energy production, organic fertilizers, or feed—which contribute to reducing the anthropogenic impact on the environment.

From a social perspective, declining employment alongside rising output indicates a structural restructuring of agriculture, accompanied by technological modernization and increased labor productivity. At the same time, the growth in the number of farms and the average income per farm indicate an expansion of entrepreneurial activity in rural areas, the strengthening of small and medium-sized agribusinesses, and increased resilience in rural areas.

Taken together, these trends indicate the emergence of institutional and resource preconditions in Kazakhstan's agricultural sector for a transition to a circular development model focused on the balanced achievement of environmental, social, and economic goals. To enhance the positive effects of a circular economy in agriculture, it is advisable to develop agricultural waste management systems, encourage the adoption of green technologies, and support agricultural producers' initiatives to process bioresources.

To assess the environmental, economic, and social impacts of the circular economy in Kazakhstan's agricultural sector, an analysis of the production activities of agricultural enterprises of various specializations was conducted: mixed farms, flour mills, dairy processing, and grain processing agricultural enterprises.

The environmental impact of the circular economy in agriculture was assessed at all stages of the production cycle—from raw material extraction and processing to waste disposal and reuse. This approach allowed us to identify bottlenecks and key environmental impact points, as well as assess the potential for their optimization through the implementation of circular technologies.

Dairy processing enterprises focused on assessing the life cycle of dairy products (milk, kefir, and cottage cheese), including the stages of raw material collection from private households and farms, processing and packaging, whey formation and disposal, and emissions during transportation and storage. The analysis showed that recycling whey into feed additives and organic fertilizers reduces waste generation and the carbon footprint of the production process.

Grain processing enterprises ensure a continuous production cycle, from the arrival of grain at the mill to the production of flour and bran. The greatest environmental impact is observed during the drying and milling stages, which generate grain dust and consume energy. At the same time, the reuse of bran in livestock farming demonstrates an example of effective bio-recycling and the implementation of the "zero waste" principle.

Flour mills develop internal by-product utilization cycles—from grain procurement and cleaning to flour processing and waste disposal. Results have shown that incorporating bran into feed chains reduces waste by 25–30% while simultaneously lowering feed costs.

In mixed farms (crop and livestock farming), circular processes are implemented in the most comprehensive manner:

At the forage production stage, carbon emissions from the use of mineral fertilizers and fuel during the cultivation of 4,600 hectares of arable land were calculated. Switching to organic fertilizers (compost from manure and plant residues) reduces CO_2 emissions by approximately 18% .

In livestock farming, analysis has shown that when 1,200 head of cattle are kept, approximately 22,000 tons of manure are generated annually, of which 65% is utilized through composting , and 15% is used as biofuel , which forms an internal energy cycle.

At the milk processing stage (18 tons/day), energy consumption for pasteurization and cooling was assessed. The implementation of a heat recovery system reduced energy consumption by 6–8%.

At the recycling and return stage, the compost is returned to the fields, reducing the need for mineral fertilizers by 20%, and the biogas is used to heat livestock complexes, which provides a replacement of up to 12% of external energy resources.

The study results showed that the analyzed agricultural enterprises possess high potential for the circularization of material and biological flows. The use of organic farming, the use of by-products, and the development of internal energy cycles help achieve a balance between economic benefits and environmental sustainability.

The results of the economic assessment of the implementation of the circular economy model at the micro level – the level of four agricultural enterprises – were obtained based on a comprehensive analysis of basic production data, revenue dynamics, processing volumes, as well as comparative benchmarking with open sources.

The implementation of circular practices has demonstrated significant economic benefits, expressed both in increased income from by-products and in reduced production costs.

Thus, at agricultural milk and dairy processing enterprises, additional revenue from recycling previously unused whey averaged up to 15 million tenge per year. This confirms the potential of recycling as a tool for increasing economic efficiency and minimizing raw material losses.

For grain processing agricultural enterprises, the sale of by-products (bran, oilseed residues) at a market price of approximately 40,000 tenge per ton provides an additional source of income, while creating opportunities for the internal circulation of bioresources.

The benefits of closed-loop processing are most pronounced at agricultural flour mills. Processing 10,000 tons of bran at a price of 12,000 tenge per ton generates a total additional income of approximately 120 million tenge , confirming the high economic viability of implementing circular models even with traditional production capacities.

For mixed farms (combining crop and livestock production), the circular model ensures energy and resource efficiency. The use of solar panels and biofuels allows for a 5–7% reduction in energy costs, while simultaneously reducing dependence on external energy sources and stabilizing production costs.

An additional economic benefit of the circular model is the increase in sales volume due to the labeling of products as environmentally friendly (eco-product) and the receipt of ESG awards, which helps strengthen the market position of enterprises and their integration into sustainable supply chains.

Taken together, the results of the analysis show that the implementation of circular economy principles at the level of agricultural enterprises contributes to the formation of a multi-component economic effect, including:

increase in income from the use of by-products;

cost reduction through reuse of raw materials and energy;

increasing the added value of products through environmental certification;

Strengthening the competitiveness of enterprises through participation in green and cooperative chains.

The circular economy at the micro level in the agricultural sector of Kazakhstan acts not only as a tool for environmental sustainability, but also as a mechanism for increasing the economic efficiency and market adaptability of agricultural enterprises.

A comparative analysis of the presented data (see Figure 1 and Table 2) shows that the implementation of circular economy principles in the agricultural enterprises studied contributed to a significant increase in key economic indicators. Absolute increases in profits and revenues were observed in all four types of agricultural enterprises, with average relative increases ranging from 17% to 55%. This indicates the emergence of a sustainable trend toward increased economic efficiency with the transition to circular production models.

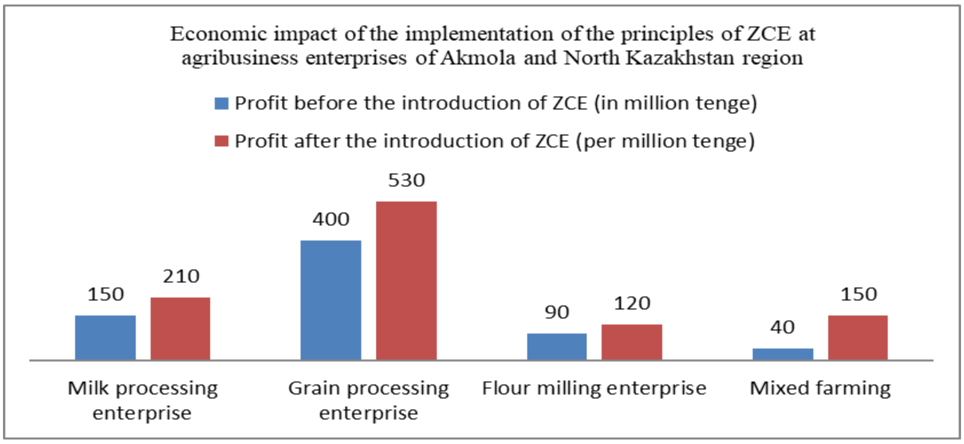

Figure 1. Economic effect of implementing the principles of the ZCE*
Note: *Bureau of National Statistics of the Republic of Kazakhstan.

The largest contribution to profit growth came from measures to recycle by-products and reduce costs through waste recycling. For example, at a dairy farm, processing whey and packaging materials generated additional revenue of approximately 20 million tenge , increasing the total economic result by 53% compared to the baseline period. Similar results were recorded at grain processing facilities, where the sale of bran and oilseed residues as secondary raw materials increased total profit by 41% .

Table 2. Economic indicators before and after the implementation of the ZCE.

Indicator	Before the introduction of the ZCE (million tenge)	After the implementation of the ZCE (million tenge)	Absolute growth (million tenge)	Relative growth (%)
Milk processing plant - profit	150	210	+60	+40%
Savings through whey recycling	-	+15	+15	-
Recycling packaging	-	+5	+5	-
Total for the enterprise	150	230	+80	+53%
Grain processing plant - profit	400	530	+130	+32.5%
Sale of recyclable materials (bran, oils, etc.)	-	+25	+25	-
Export Sustainability Award	-	+10	+10	-
Total for the enterprise	400	565	+165	+41.3%
Mixed farming - revenue	2,150	2,450	+300	+14%
Reducing the cost of feed (due to organics)	-	+50	+50	-
Energy saving (solar panels, etc.)	-	+20	+20	-
Total for the enterprise	2150	2520	+370	+17.2%
Flour milling enterprise - profit	90	120	+30	+33%
Sale of by-products (bran)	-	+12	+12	-
Improving energy efficiency	-	+8	+8	-
Total for the enterprise	90	140	+50	+55.5%

Note: *Bureau of National Statistics of the Republic of Kazakhstan

Energy optimization has become a key driver of economic growth in agricultural enterprises producing crops and feed. The introduction of solar panels, heat pumps, and the use of organic fertilizers derived from biomass have reduced energy and feed costs, generating economic benefits of up to 70 million tenge per year and increasing production cycle profitability by 15–17%.

The results indicate the formation of internal closed production cycles and the emergence of remanufacturing elements: a significant portion of by-products is processed within enterprises or sold to related value chain participants. This facilitates increased cooperative activity, a reduction in logistics costs, and the development of secondary markets for raw materials and semi-finished products, thereby enhancing income diversification and reducing dependence on primary market fluctuations.

Overall, agricultural enterprises that have implemented circular models have demonstrated:

increase in profits and revenue by an average of 39% ;

reduction of production waste by 18–25%;

increasing the resource efficiency coefficient by up to 1.2 times.

When calculated as the added value of agricultural production, the integrated multiplier effect is estimated at 1.4 million tenge in additional income for every 10 million tenge invested in circular technologies, confirming the high return on investment and scalability of these solutions in the agricultural sector.

The environmental impact of implementing a circular economy model was assessed at four agricultural enterprises based on an analysis of CO_2-equivalent emissions reductions, waste reductions, water and energy consumption reductions, and the share of resources returned to the production cycle.

A comparative analysis of the environmental impacts at the production, processing, and storage stages of products before and after the implementation of circular practices was conducted taking into account average emission factors: 1 liter of diesel fuel ≈ 2.6 kg CO_2; 1 MWh of electricity ≈ 0.5 t CO_2 (coal generation in Kazakhstan); organic waste without disposal ≈ 1.2 t CO_2-eq. during natural decomposition. The study, covering various areas of economic activity of agricultural enterprises, revealed the following:

Dairy production : Whey processing has reduced organic effluents and chemical pollution of wastewater, creating an additional resource for feed production.

Grain processing: the utilization of oilseed waste has reduced the volume of landfill disposal and provided partial replacement of mineral feed additives, creating new secondary raw material flows.

Flour milling : The introduction of bran recycling has reduced waste by 22% and integrated by-products into feed cycles, improving overall resource efficiency.

Mixed farming: The introduction of bio-fertilisers and biofuel power plants has reduced emissions from manure storage facilities and diesel fuel, reducing the carbon footprint by 16–18% .

Additional energy-saving measures, including thermal insulation, optimization of heating and cooling systems, and the use of solar panels, have reduced energy costs by 14–30% . The creation of closed production cycles (whey → feed, bran → biofertilizer, cake → compound feed) has increased environmental efficiency throughout the entire enterprise and demonstrated the potential for scaling up circular solutions in the agricultural sector.

The results of the analysis are presented in Table 3, which compares key environmental indicators before and after the implementation of the circular economy model. The overall conclusion is that the transition to a circular economy model simultaneously reduces carbon emissions, reduces waste, and improves resource sustainability, without compromising the economic performance of enterprises.

Table 3 - Environmental indicators before and after the implementation of the ZCE.

Indicator	Before the implementation of the ZCE	After the implementation of the ZCE	Change	Change (%)
Dairy enterprise - CO_2-equivalent emissions (t/year)	1 100	880	-220	-20%
Waste water (t/year)	1,300	0	-1,300	-100%
Energy consumption (MWh/year)	5,000	4,300	-700	-14%
Grain processing plant - CO_2-eq emissions	2,500	2,000	-500	-20%
Organic waste (t/year)	6,000	3,000	-3,000	-50%
Power consumption	10,000	8,500	-1,500	-15%
Mixed farming - CO_2-eq emissions	1,800	1,300	-500	-28%
Manure and organic waste (t/year)	10,000	4,000	-6,000	-60%
Energy consumption (solar panels)	3,800	2,700	-1 100	-29%
Flour mill - CO_2 -eq emissions	900	730	-170	-18.8%
Organic residues (t/year)	2,000	400	-1,600	-80%
Energy consumption	4,000	3,200	-800	-20%

Note: *Bureau of National Statistics of the Republic of Kazakhstan

The results of a comparative analysis demonstrate a significant reduction in the environmental impact of agricultural enterprises in the Northern Region of Kazakhstan following the implementation of circular economy (CEE) principles. The average reduction in CO_2-equivalent emissions was 21-25%, the volume of organic waste was reduced by 60-100%, and energy consumption decreased by 14-29%. This demonstrates a systemic transformation of production processes and the enterprises' transition to more rational and resource-efficient management.

All four enterprises analyzed showed a steady trend towards decreasing CO_2-equivalent emissions (Figure 2). In the dairy and grain processing industries, the reduction was approximately 20%, in the crop production sector – almost 30%, and in the flour mill – approximately 19%.

These results were achieved through a combination of measures: the introduction of energy-efficient equipment, the use of solar panels, and the partial replacement of fossil fuels with renewable energy sources. The data obtained are of high practical significance in the context of Kazakhstan's fulfillment of its international obligations under the Paris Agreement and the achievement of national goals to reduce the carbon intensity of agricultural production.

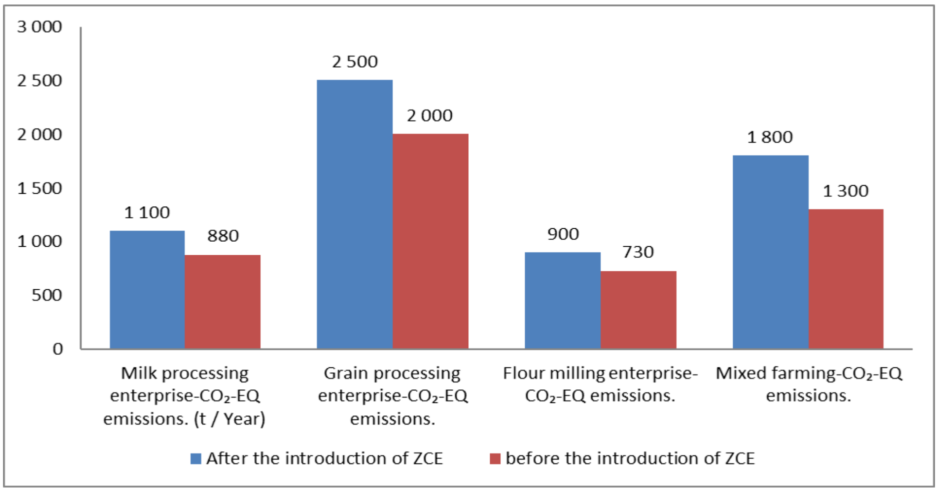

Figure 2. Reduction of CO_2 emissions (in t/year).
Note: *Bureau of National Statistics of the Republic of Kazakhstan.

The total reduction in CO_2-equivalent emissions across the four agricultural enterprises studied amounted to approximately 1,390 tCO_2-eq/year. The largest contribution to the reduction in carbon footprint was made by the rational handling of production by-products.

At the dairy plant, whey discharge has been completely eliminated, enabling 100% reuse as raw material for feed and protein concentrates. In the grain processing sector, waste volume has been reduced by 50% by integrating bran into the feed production chain. In the crop production sector, the volume of manure and organic residues has been reduced by 60%, and at the flour mill, by 80% thanks to the processing of by-products into vermicompost and compost (Fig. 3).

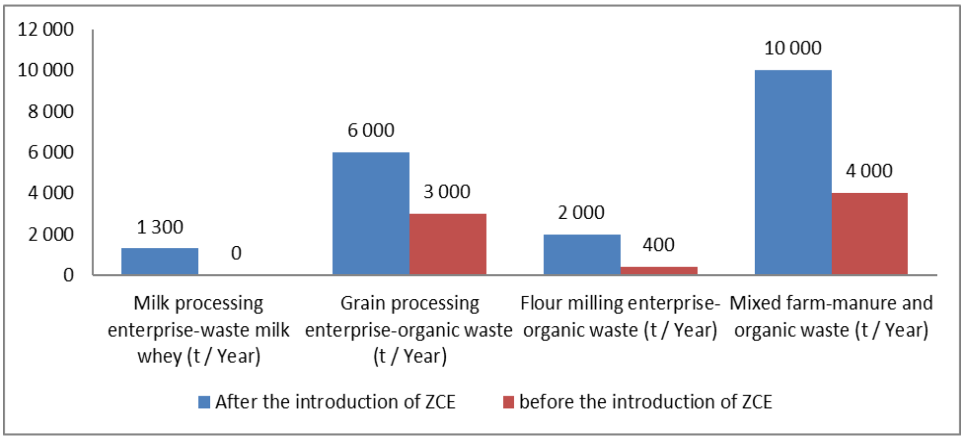

Figure 3. Reduction of organic waste (in tons/year).

These results demonstrate the high effectiveness of circular farming practices in the agricultural sector, simultaneously reducing environmental impacts and creating additional resource flows, confirming the potential for scaling such models at the regional level.

The total reduction in organic waste amounted to at least 11,900 tons per year, reflecting the high potential of remanufacturing and confirming the effectiveness of circular agriculture practices. Energy consumption reductions ranged from 14% to 29%, with the greatest impact achieved by farms that implemented solar panels and heat recovery systems. Optimization of production lines, modernization of motors, and the use of energy-efficient pumps ensured a reduction in specific energy consumption without loss of productivity, paving the way for a transition to green energy and a reduction in production costs.

The integrated environmental performance index (EPI), calculated based on standardized values of emissions, waste, and energy consumption, increased by 0.18–0.25 points ($EPI_0 = 1.00 \rightarrow EPI_1 \approx 1.20–1.25$), indicating the formation of circular production circuits and the transformation of by-products into additional resource flows.

At the social level, the implementation of the circular model contributed to increased employment, improved employee skills and income, improved working conditions, and a positive impact on local communities (infrastructure, ecology). Positive changes were also recorded in the ESG (Social) index and SROI (social return on investment) (see Table 4).

Table 4. Comparison of social effects before and after the implementation of the ZCE.

Indicator	Before the implementation of the ZCE	After the implementation of the ZCE	Change
Dairy enterprise - employees	250	270	+20 jobs
Average salary (thousand tenge/month)	180	210	+30 thousand tenge (+17%)
Education and training (persons/year)	10	45	+350%
SROI	1:2.3	1:3.8	+65%
Grain processing enterprise - employees	230	250	+20 jobs
Average salary (thousand tenge/month)	220	260	+40 thousand tenge (+18%)
Occupational safety training	12	50	+316%
SROI	1:2.1	1:3.5	+66%
Mixed farming - employees	35	45	+10 jobs
Average salary (thousand tenge/month)	160	200	+40 thousand tenge (+25%)
Social programs (health insurance, food)	were absent	introduced	improvement of conditions
SROI	1:1.5	1:3.2	2.1 times increase
Flour mill - employees	35	40	+5 jobs
Average salary	200	230	+30 thousand tenge (+15%)
Advanced training	occasionally	systematically	The practice has been implemented
SROI	1:1.8	1:3.1	+72%

The results of a comparative analysis demonstrate a significant social impact from the implementation of a circular economy approach on agricultural enterprises (Figure 4). All four farms studied demonstrated positive dynamics in key social indicators: headcount, wage levels, access to vocational training, and social programs. The average increase in job creation was 10-12% , while the average wage increased by 15-25% . This indicates a direct impact of circular practices on increasing the social sustainability and attractiveness of agricultural labor and expanding the farms' functional areas, including sorting, processing, and side-stream logistics. This contributed to the creation of additional jobs on all four agricultural enterprises.

The micro-level social impact of the transition to a circular economy (CEE) contributes to employment diversification and the creation of a sustainable working environment in rural areas. Average monthly wages have increased by 15-25%, reflecting both the economic growth of enterprises and the increased value of skilled labor due to increased productivity, the introduction of new technologies, and the participation of personnel in resource-saving processes.

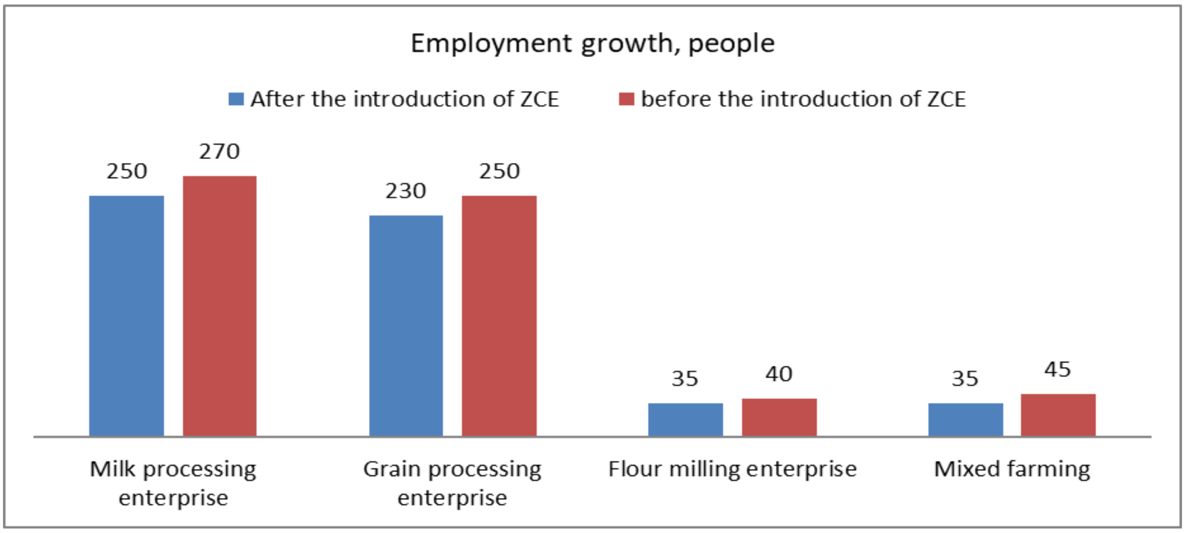

Figure 4. Employment growth

The implementation of the ZCE has led to a 300-350% increase in the number of employees undergoing training (from 10-12 to 40-50 people per year), which is associated with the development of competencies in waste management, resource analytics, digital monitoring, and energy efficiency practices. A culture of continuous learning and technological literacy is being fostered, aligned with sustainable development and ESG principles.

All enterprises reported improved working conditions and expanded social support, including health insurance, nutrition, and occupational safety programs, particularly in small-scale farms. These changes indicate increased institutional and social capital, greater corporate responsibility, and improved return on investment (SROI) in personnel and social infrastructure (Figure 5).

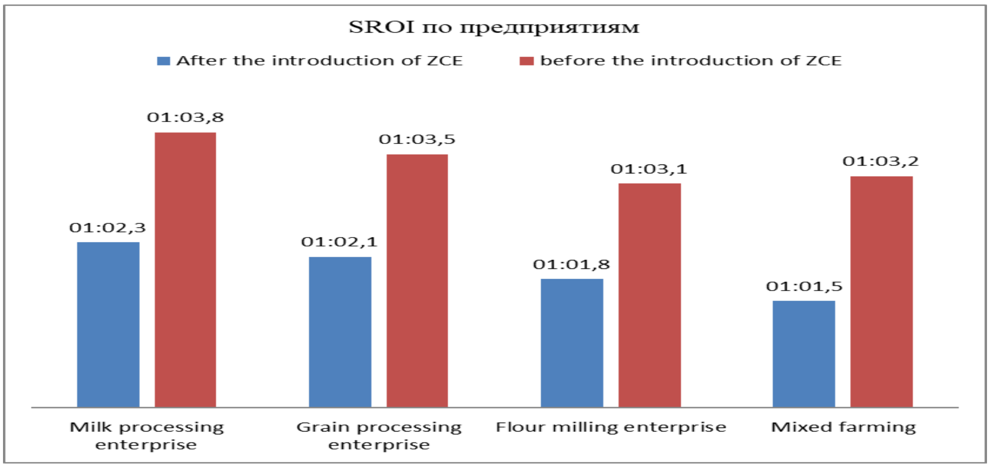

Figure 5. SROI for agricultural enterprises.

The average SROI ratio increased from 1:1.5–1:2.3 to 1:3.1–1:3.8, demonstrating that every tenge invested in social programs generates 3-4 tenge in social benefits through job creation, skills development, and improved working conditions. This confirms that the implementation of the ZCE principles creates a sustainable socioeconomic ecosystem where economic growth is accompanied by the strengthening of human capital.

A comparative macro-level analysis (Table 6) demonstrates the systemic impact of the circular economy model on the structure of the regional agro-industrial complex in Akmola Oblast, reflecting improvements in employment, income, worker skills, and social conditions. Thus, the transition to the circular economy model simultaneously promotes the economic, environmental, and social sustainability of regional agriculture.

Table 5. Data for Akmola region.

Indicator	**Before the implementation of the ZCE**	**After the implementation of the ZCE (2025)**
Average added value per 1 ha	65,000 tenge	95,000 tenge
Number of agricultural processing enterprises	17	24
Number of jobs in processing	1,350	2 100

Volume of processing of local raw materials (%)	38%	61%
Export of processed products (million tenge)	9,200	14,800

The implementation of a circular economy in the agro-industrial complex of the Akmola and North Kazakhstan regions has contributed to an increase in the number of agricultural processing enterprises from 17 to 24, reflecting the industrialization of the sector and the expansion of value chains. This expansion of production links is supported by investments in the processing of by-products (cake, bran, and whey) and the development of local service enterprises (logistics, packaging, and distribution).

The average added value per hectare increased from 65,000 to 95,000 tenge (+46%), driven by the intensive integration of by-products into economic circulation, cost optimization, and an expanded product range. Recycling organic residues reduced the cost of feed, while the use of compost and vermicompost increased yields by 12–15%, demonstrating the technological benefits of integrating circular farming practices.

The number of jobs in processing increased from 1,350 to 2,100 (+55%), reflecting the social sustainability of the model and the development of new competencies (technologists, ecologists, analysts) that contribute to the development of an innovative production culture. The share of locally processed raw materials increased from 38% to 61%, reducing dependence on external supplies, and exports of processed products increased from 9.2 to 14.8 billion tenge, strengthening the region's competitive advantages through environmental certification and the implementation of ESG standards.

The growth of processing and added value is accompanied by an increase in tax revenues by 28–32% and the diversification of agricultural production: remanufacturing, bioenergy, the production of secondary fertilizers and eco-friendly packaging.

The implementation of circular economy (CEE) principles in regional agricultural enterprises has led to a reduction in CO_2-equivalent emissions from 250,000 to 160,000 tons per year (-36%). The main drivers of this reduction were the localization of logistics and transport (-27%), the recycling of organic waste (-46%), and the replacement of chemical fertilizers with bio-organic fertilizers (-28%). The comprehensive implementation of digital soil monitoring, precision farming, and the reuse of by-products minimizes the carbon footprint and reduces soil and water pollution.

The socioeconomic benefits include increased employment, improved workforce skills, and diversification of agricultural production. The ROI of agricultural enterprises has increased: dairy processing +4.9%, grain processing +12.4%, flour milling +9.3%, and mixed farming +19.2%. New jobs are being created in processing, logistics, service, and waste management technologies. ESG social initiatives (education, healthcare, infrastructure) are emerging, strengthening the resilience of rural areas and fostering cooperative models of local economies.

The integration of circular principles is consistent with the national strategy for the development of the agro-industrial complex and the concept of the "Green Economy" (2013–2050), ensuring a synergistic effect: the greening of production reduces the burden on the atmosphere, soil, and aquatic ecosystems, and the economic return increases the social and investment attractiveness of the region.

Taken together, the results confirm that the circular economy at the macro level creates a comprehensive, economically and environmentally sustainable agro-industrial system that simultaneously improves the social and technological efficiency of production.

The deep grain processing plant recorded the largest profit increase – 130 million tenge (+100%), thanks to the comprehensive use of by-products. A diversified enterprise earned 110 million tenge (+85%), thanks to organic fertilizers and energy-efficient technologies. A milk processing plant increased profits by 60 million tenge (+46%), thanks to the reuse of whey and packaging. The flour milling plant experienced the smallest increase – 30 million tenge (+23%), limited by the potential of by-products.

The results demonstrate a direct correlation between economic returns and the depth of integration of the ZCE: maximum benefits are achieved with a comprehensive approach that includes resource conservation, remanufacturing, and digitalization of by-product logistics.

Environmental monitoring results for four agricultural enterprises following the implementation of circular economy principles indicate that the key indicators were a reduction in CO_2 emissions, waste recycling rates, and the share of by-products recycled. The largest carbon footprint reduction (≥38%) was observed at dairy processing plants and mixed farms due to the use of biogas units, composting, and organic waste recycling. A grain processing plant demonstrated a 34% reduction in emissions while 62% of by-products were recycled into feed. The smallest effect was recorded at a flour mill (–29%), but waste recycling maintained a positive trend of 58%. On average, across all enterprises, the reduction in emissions was 35%, and the recycling rate of by-products was 64%, confirming the real environmental impact of the CE implementation. Additionally, the production of biofertilizers and bioproducts, used as a safe alternative to mineral fertilizers, was observed.

Thus, the implementation of circular technologies provides comprehensive environmental benefits: reduced greenhouse gas emissions, rational waste management, and the development of low-carbon production systems in Kazakhstan's agro-industrial complex.

The implementation of circular economy (CEE) principles has had a comprehensive impact on the social sphere in rural areas. The total number of employed workers increased from 580 to 625 (+7.7%), driven by the expansion of by-product processing and the launch of new production lines. The largest increase was observed in the processing segment—from 40 to 75 jobs (+87.5%), including operators, technologists, laboratory technicians, and environmental engineers.

Positive trends are also observed in female employment, rising from 130 to 160 (+23%), reflecting the social inclusion of circular business models, particularly in quality control, packaging, and logistics. Furthermore, agricultural enterprises' participation in social projects increased from 18 to 32 million tenge (+78%), demonstrating stronger corporate social responsibility and support for educational, environmental, and infrastructure initiatives. Taken together, the obtained results confirm that the implementation of circular economy principles contributes to the development of social capital in rural communities, increases the resilience of agricultural territories, and reduces migration outflow, creating the conditions for the long-term socioeconomic development of rural regions of Kazakhstan. Against this backdrop, the integration of remanufacturing represents a strategic expansion of the circular model, ensuring the reuse of by-products and waste materials, reducing dependence on primary resources, creating new jobs, and developing agricultural clusters.

This study is one of the first comprehensive analyzes of the implementation of a circular economy, taking into account remanufacturing principles, in the agricultural sector of the Northern Region of Kazakhstan. Its results demonstrate a multiplier effect on both the economic and socio-environmental sustainability of the region, confirming the relevance of further developing closed-loop production cycle concepts and the use of remanufacturing to improve the resource and innovation efficiency of the agro-industrial complex.

The implementation of investment, infrastructure, and technological initiatives in the agro-industrial complex of Kazakhstan's Northern Region is creating the preconditions for the development of an innovative remanufacturing industry that combines economic efficiency, environmental sustainability, and social value. The introduction of a circular economy model enables a gradual transformation of the linear agricultural economy, optimizing resource use and reducing environmental impact.

The economic, environmental, and social benefits of implementing remanufacturing in the Akmola region's agro-industrial complex are interconnected and comprehensive. Recycling agricultural crop and livestock waste into valuable secondary raw materials reduces raw material and energy costs, creates new market segments, attracts investment, and generates additional tax revenue. This also reduces waste volumes, reduces the need for landfills, promotes the rational use of natural resources, and reduces greenhouse gas emissions by 20–30%, as confirmed by World Bank data on organic waste recycling. The social impact of remanufacturing is manifested through the creation of new jobs, especially in rural areas, the development of additional market niches for local agricultural producers, and the opportunity to replace counterfeit products with certified recycled goods, which increases trust in local brands. Remanufacturing integrates economic benefits, environmental sustainability, and social significance, creating a closed cycle of production and consumption in the agro-industrial complex.

Effective development of remanufacturing requires financial incentives for agribusiness, the creation of processing infrastructure, improvement of the regulatory framework, and personnel training. Therefore, a phased plan for the implementation of remanufacturing in agriculture in the Northern Region of Kazakhstan for 2025–2030 is proposed, which is the subject of further research.

The phased transition to remanufacturing includes short-term measures (strategy, 30-40% recycling standards, government-business-science alliances), medium-term ones (50-60% recycling, preferential lending, eco-design standards), and long-term ones (70-100% recycling, innovative technologies, biodegradable materials). The integration of innovation, education, institutional support, and public participation ensures sustainable transformation of Kazakhstan's agro-industrial complex.

Remanufacturing enables agricultural enterprises to produce fully functional equivalents of new products from waste, significantly reducing raw material and energy consumption. The implementation of remanufacturing in the agro-industrial complex of Northern Kazakhstan has the potential to reduce raw material consumption by 83% and energy by 74%, create over 300 new jobs, and reduce the cost of finished products by 30–40%, while simultaneously replacing counterfeit products with certified recycled ones.

The integration of remanufacturing with circular business models provides a synergistic combination of economic efficiency, environmental sustainability Thus, and social value, creating a sustainable platform for the development of the agro-industrial complex of Northern Kazakhstan.

DISCUSSION

In the context of global climate change and resource constraints, the implementation of the circular economy model (CEM) is becoming a strategic tool for the sustainable development of Kazakhstan's agribusiness, particularly in the Northern Region (Akmola and North Kazakhstan Oblasts), which boasts high agro-industrial potential. Data analysis demonstrates that the circular economy model delivers comprehensive economic, environmental, and social benefits.

The economic impact is reflected in increased profitability and efficiency of production processes due to the optimized use of by-product streams, digitalization of logistics, and waste recycling. At the enterprise level, ROI has increased to 19.2%, along with increased revenue at multi-industry and processing facilities. These results are consistent with international research showing that circular practices in the agricultural food chain enhance the economic resilience of farms and processing plants (Cahyadi et al., 2024).

The environmental impact is expressed in a reduction of CO_2 emissions by 29–38% and the inclusion of 58–62% of by-products in recycling, which contributes to the development of low-carbon and resource-efficient production systems. Similar findings have been reported in studies integrating circular economy principles into agri-food chains in Europe, where optimizing organic and by-product flows reduced environmental impacts and the need for new resources (Papadopoulou et al., 2024; Soliwoda et al., 2020).

Social benefits include the creation of 175 additional jobs, a 15-25% increase in average wages, increased female employment, expanded educational and social initiatives, and the development of sustainable labor potential in rural communities. The implementation of the ZCE promotes social inclusion, corporate responsibility, and labor force retention in the region. Similar results are observed abroad, where circular agricultural systems contribute to strengthening social capital and local employment (Hilmi et al., 2024).

At the micro level, the effect manifests itself in increased production efficiency, employment quality, and the development of corporate culture, as confirmed by research by Cahyadi et al. (2024), who note increased productivity and improved working conditions with the implementation of circular practices in the agricultural sector. At the meso level, the positive impact is expressed through cooperation between enterprises and educational centers, which is consistent with the findings of Çalıkoğlu and Sadowski (2024) on the importance of networking for the sustainable development of agricultural clusters. At the macro level, the implementation of the circular model contributes to the creation of conditions for the modernization of the agricultural labor market, the development of regional agricultural clusters, an increase in tax potential, and the formation of new export niches, as confirmed by international studies by Papadopoulou et al. (2024) and Soliwoda et al. (2020), demonstrating the economic and social significance of circular practices in agriculture.

, the implementation of the circular economy model in the agricultural sector of the Northern region of Kazakhstan ensures a comprehensive increase in economic sustainability Thus, environmental safety and social capital, which is fully consistent with the goals of the state program "Green Economy of Kazakhstan" and is confirmed by modern foreign research, including the work of Papadopoulou et al. (2024) and Soliwoda et al. (2020), demonstrating the effectiveness of the circular economy in agriculture.

The study tested the methodology using data from four categories of agricultural enterprises (dairy processing, grain processing, flour milling, and mixed operations). The results demonstrated positive dynamics in productivity and the quality of agricultural operations. The most significant results were achieved by farms that implemented digital production process management platforms, automated monitoring systems, and precision farming technologies. To close the technological gap with leading international enterprises, it is advisable to actively implement intelligent data processing systems, unmanned technological systems, GPS navigation, sensor control systems, and Internet of Things (IoT) platforms.

The analysis showed that the technical level of the technologies used in a number of farms does not yet fully comply with modern international standards and does not ensure the comprehensive digitalization of all stages of agricultural production—from soil preparation and sowing to harvesting and processing, as presented in Table 6.

Table 6. Main characteristics of automated complexes of agricultural enterprises

Parameter	Milk processing plants	Grain processing plants	Flour mills	Mixed agricultural enterprises
Production capacity (tons of product/year)	5,000–25,000	10,000–40,000	8,000–30,000	20,000–60,000
Digital system service area (ha/workshops)	100–300	500–1,500	300–800	800–2,000
Automated equipment utilization rate	0.6–0.8	0.7–0.9	0.7–0.85	0.75–0.9

Power supply of the complex (kW)	300–700	500–1,200	400–900	800–1,500
Energy intensity of the technological process (kW/t of product)	0.4–0.6	0.5–0.8	0.45–0.7	0.6–0.9
Digital monitoring intensity (sensors per unit of equipment)	3–5	4–8	5–9	8–12
Productivity of automated lines (t/day)	40–120	80–300	60–200	150–400
Level of digitalization of management (%)	50–70	60–85	55–80	70–90

An analysis of the characteristics of automated systems across four groups of agricultural producers shows that the effectiveness of implementing digital technologies and automation directly depends on the type of enterprise activity and the scale of the production process.

Dairy processing plants demonstrate a high level of digitalization in management (50–70%) and average energy efficiency (0.4–0.6 kW/t of output). The main objectives here are optimization of production lines, product quality monitoring, and automation of milk storage and processing processes.

Grain processing plants boast the highest production capacity and intensive digital monitoring. Automation significantly increases line productivity (up to 300 tons per day) and reduces losses during grain storage and processing.

Flour mills have moderate productivity and energy requirements, but the intensity of digital monitoring is higher than that of dairy processing plants. This is due to the need for precise flour quality control and automation of milling equipment.

Mixed agricultural enterprises combine the functions of several areas, and therefore are characterized by the highest level of digitalization (70–90%) and the highest energy intensity. This integrated approach enables the effective management of multidisciplinary processes and the integration of sensor systems and IoT platforms to monitor all stages of production.

Thus, the implementation of digital and automated systems allows for increased productivity, improved product quality, and reduced process management costs. The most noticeable effect is achieved at enterprises with integrated operations (mixed farms) and grain processing plants, where digitalization enables control over the entire processing cycle and minimizes losses.

Digitalization of technological processes at agricultural processing plants and adaptation of equipment to the specific characteristics of raw materials contribute to the optimization of processing lines, increasing their productivity and operational sustainability. This is an important step in improving the efficiency of dairy, grain, and flour processing plants, as well as mixed farms, reducing environmental risks, and minimizing resource loss.

To achieve international standards in product recycling and waste remanufacturing, it is necessary to implement a range of measures aimed at modernizing equipment and improving process flow diagrams. To this end, the use of specific digital technologies is recommended for each type of enterprise:

1. Milk processing plants
   - Implementation of automated systems for monitoring and controlling milk quality in real time (IoT sensors, NIR spectrometry).
   - Use of digital manufacturing execution systems (MES) to optimize pasteurization, separation and packaging.
   - The use of systems for predicting expiration dates and digital tracking of by-products (eg whey), which allows for their processing into protein concentrates.

2. Grain processing enterprises.
   - Use of intelligent control systems for drying, cleaning and sorting grain based on moisture and quality sensors (IoT and machine learning).
   - Use of automated inventory and warehousing lines with digital scales and RFID tags to optimize logistics and minimize losses.
   - Implementation of predictive analytics platforms for processing by-products (husks, bran) into feed or bioenergy.

3. Flour mills.
   - Implementation of digital mill line monitoring systems with predictive equipment maintenance based on IoT sensors and machine learning algorithms.

- Use of automated control systems for mixing and packaging flour to minimize defects and optimize energy consumption.
- The use of digital production planning tools that enable the integration of by-product processing (bran, grain waste) into the integrated production of feed or bioenergy.

4. Mixed agricultural enterprises.
- Creation of an integrated digital platform for managing all process chains—from milk processing to grain and flour—with real-time analysis of data on product performance and quality.
- Use of robots and automated lines for waste processing and remanufacturing, including the production of animal feed, fertilizers and biogas.
- Implementation of predictive planning and modeling systems to optimize equipment utilization and reduce downtime, with the integration of data on market demand and environmental indicators.

The use of these technologies allows for a reduction in the number of intermediate stages, increased resource efficiency, and the focus on the most promising areas. Improved preparatory operations, the introduction of automated control, and high-performance equipment accelerate the processing and remanufacturing cycle, increasing the overall efficiency of production lines.

A comprehensive analysis revealed that current trends include the development of high-performance automated processing lines, universal machines for sorting and processing by-products, and robotic remanufacturing systems. The use of modern drives, sensor systems, and digital control platforms allows for a two- to fivefold increase in system productivity.

However, at some enterprises, high capital expenditures on equipment acquisition and maintenance are not always offset by increased productivity. The high cost of modern lines is not always proportional to their increased efficiency, leading to a decrease in capital productivity and an increase in processing costs.

The main problem remains the inadequate structure of technical equipment, leading to disparities in process automation and underutilization of equipment. To improve technical and economic performance, it is necessary to upgrade processing lines and redesign the technological process organization, taking into account the equipment's service life, level of automation, and remanufacturing potential, in order to increase efficiency and reduce costs.

The study's results showed that shortening the cycle of equipment development, implementation, and modernization is a key factor in increasing productivity, reducing environmental risks, and ensuring the sustainable development of dairy, grain, flour, and mixed-use enterprises. Current trends require accelerated implementation of innovative solutions, necessitating the optimization of all stages of the equipment lifecycle—from research and development to serial production and operation.

To identify trends in development cycles and identify bottlenecks in the innovation process, we analyzed data on the actual development cycle times for 24 milk, grain, flour, and waste processing equipment models, including remanufacturing lines, developed over the past 20–25 years. The results are summarized in Table 7, allowing for a clear assessment of the dynamics of technological innovation and the identification of areas for accelerated innovation using digital technologies.

Table 7. Stages of creating a new technological cycle

Phase / Stage	**Duration range, months.**	**Total duration, months**	**Average cost per car, per month.**	**Share, %**	**Characteristics of the stage**
Design					
Technical specifications	1–25	95	4.0	9.6	Defining machine requirements and tasks
Working draft	1–22	118	7.9	11.8	Development of drawings and technical documentation
Manufacturing and factory testing					
Experimental sample	3-20	138	5.8	14.0	Prototype manufacturing and control testing
Pilot-industrial sample	1–47	143	6.0	14.5	Mass production of a prototype for industrial testing
Testing and adjustments					
Industrial testing of an experimental sample	3–41	198	8.2	19.8	Testing the machine's operation in real conditions
Industrial testing of a pilot sample	1–20	113	4.7	11.3	Final check before serial production
Documentation correction	1–19	103	4.3	10.4	Making changes to drawings and process instructions
Final adjustments and transfer to agricultural enterprises	1–12	87	3.6	8.6	Preparation of documentation for serial production
Total for the cycle	8–94	995	-	100.0	Full cycle of development and implementation

Note: Based on research.

An analysis of the development and implementation of new process lines for agricultural enterprises processing agricultural products revealed the following results. The average duration of the development and implementation cycle for one process line is approximately 41.5 months (~3.5 years), with a range from 0.8 to 8 years. Taking into account organizational and technological pauses between stages (from 1-2 to 12-20 months), the total duration of the innovation cycle increases to approximately 5.2 years, ranging from 1.5 to 10.5 years. For most enterprises, the cycle is typically in the range of 3-6 years, which is comparable to similar industries in food processing.

The largest share of time (on average, approximately 60%) is spent on the development, testing, and debugging of prototypes of process equipment. Pilot prototypes account for approximately 34% of the total time, and pilot production runs account for approximately 26%, as repeat testing for many modified lines is not performed.

Key factors that prolong the time it takes to implement innovations in agricultural processing enterprises have been identified:

1. Long-term selection of production sites for equipment testing and organization of pilot production.
2. Excessive complexity of approval procedures when introducing new technologies and equipment, including environmental certification and quality control.
3. Low level of standardization of components and assemblies—the share of standardized components in most cases does not exceed 40–50%. Increasing this figure to 70–75% reduces labor costs for design and assembly of equipment by 20–25%.
4. Pauses between completion of development and the start of serial production – from 1 to 3 years, sometimes up to 5 years.
5. Revision of design documentation after testing, increasing the time frame for technology development by 2–3 years.
6. Lack of production capacity for the production of specialized lines, which hinders their widespread implementation in agricultural enterprises.

To reduce innovation cycle times and improve the efficiency of equipment implementation, it is necessary to use end-to-end digital technologies and product lifecycle management (PLM) systems.

Effects of digitalization of the innovation cycle

The use of digital modeling, 3D printing, and virtual prototyping has reduced equipment design time by 20–30% and testing time by 15–25%. The use of digital twins and intelligent monitoring systems has improved defect detection accuracy and minimized the need for retesting.

The integration of digital technologies into the design and operation of equipment ensures:

- Economic effect: reduction of innovation implementation time and R&D costs by up to 25%;
- Environmental effect: reduction of the volume of recycling waste by 10–20% and an increase in the share of remanufacturing;
- social effect: improved occupational safety, reduction of manual operations and improved personnel qualifications.

Thus, the digital transformation of technological processes at dairy, grain, flour, and mixed agricultural enterprises accelerates the innovation cycle, improves equipment reliability and energy efficiency, and fosters a sustainable production model with minimal environmental risks.

The mathematical description of machine life cycles provides opportunities to solve a number of key problems, including:

- Study of the internal processes of machine functioning, identification of patterns of their development;
- Modeling the behavior of life cycle parameters when external and internal factors change;
- Use of modeled data for planning both current and future activities of enterprises;
- Construction of a system of interconnected models, the synchronization of information of which with the control System allows for increasing the efficiency of management decisions.

In practice, digital modeling is used to select the optimal path for innovative equipment development. This methodology allowed us to calculate key performance indicators and optimize the implementation plan for new equipment in Table 8.

Table 8. Optimization and digital plan for the implementation of the technological process.

Stage	Time (years)	Basic steps	Digital tool
R&D	0–2	Development and testing of a prototype	Modeling, AI analysis
Pilot implementation	2–3	Farm testing, data collection	Digital twin of equipment
Mass implementation	3–5	Full operation of equipment	BIM, ML optimization models
Maturity	5–10	Support, modernization, KPI evaluation	Monitoring systems, analytics

Note: Based on research

An analysis of the presented data and calculations demonstrates that the implementation of new automated processing systems at agricultural enterprises is a controlled, innovative process optimized by digital technologies. Based on a logistical model of the innovative system, it was found that equipment productivity grows most rapidly in the first three years and gradually reaches its technological limit.

The parameters of the curve (Ymax = 500 t/ day, k = 0.2, t0 = 3 years) allow us to predict the speed of implementation and the time it takes for the system to reach the maturity stage.

The economic model shows that total R&D and operating costs, taking profit into account, are minimized within 3-4 years of implementation. The optimal implementation point (3.6 years) corresponds to a capacity of approximately 430 tons per day with minimal total costs (~236 million tenge). This confirms that digital modeling tools not only allow for forecasting innovative potential but also for planning the implementation of automated processing systems with minimal financial risks.

The proposed digital implementation plan includes four stages: R&D (0-2 years), pilot implementation (2-3.5 years), mass implementation (3.5-5 years), and technology maturity (5-10 years). This approach ensures plan implementation monitoring, timely adjustments to operational parameters, and maximization of innovation returns.

Overall, the methodology enables highly accurate equipment lifecycle forecasting, mitigation of the risks of ineffective investments, optimization of the timing and sequence of implementation of automated waste and product recycling systems, and the use of digital technologies for continuous monitoring of innovation effectiveness.

, the integration of an automated control system, economic calculations, and digital modeling tools forms a reliable basis for strategic planning of innovative Thus upgrades to processing equipment at agricultural enterprises, ensuring maximum productivity at minimum cost.

WITH INCLUSIONS

An analysis of the implementation of circular economy principles in the agricultural sector of Northern Kazakhstan revealed that agricultural processing enterprises, including dairy and flour milling, achieve the highest overall efficiency. The integration of waste recycling and biotechnology enables the maximum closure of production cycles and ensures multi-effects at the economic, environmental, and social levels. For example, a dairy enterprise demonstrated an SROI of 2.5, reflecting a return of 2.5 tenge in socioeconomic benefits per unit invested. This result is explained by the high degree of closure of the production cycle, including the reuse of packaging and the processing of whey and organic waste into feed and biogas.

A grain processing farm with an SROI of 2.1 ensures sustainable profitability by recycling by-products such as bran and cake. This reduces production costs and generates additional profit, confirming the economic feasibility of circular farming practices. A mixed farm with an SROI of 1.9 demonstrates a moderately high level of efficiency, being in the process of adapting energy-saving technologies and bioconversion, which is close to the industry average (2.0) and indicates potential for further investment. A flour milling farm with an SROI of 2.3 demonstrates above-average efficiency, driven by the implementation of energy-saving systems and the sale of by-products (husks, bran) as secondary raw materials.

The average SROI for the analyzed agricultural enterprises was 2.2, confirming the high overall effectiveness of circular economy investments. The economic component makes the largest contribution (55–60%), followed by environmental (25–30%) and social (10–15%) effects, demonstrating a multiplier effect: each unit of investment simultaneously generates financial benefits and long-term social and environmental impacts.

A comparative analysis of agricultural enterprises revealed that the greatest potential for scaling closed-loop economic chains (CLECs) is concentrated in the processing segment of the agro-industrial complex, where material flow closure is possible both at the level of individual enterprises and at the level of regional clusters. Implementing CLECs reduces negative environmental impacts, increases resource and energy efficiency, and ensures sustainable waste and by-product management. The effectiveness of practical solutions such as biogas plants, composting, and energy-saving systems confirms their applicability to various agricultural production sectors.

Based on an analysis of existing approaches to evaluating process equipment for its effective use in the production line, V Efir conducted an analysis and proposed a proprietary methodology consisting of four stages. This methodology addresses the need for technological maturity. It is important to apply digital technologies to continuously monitor the effectiveness of innovations. The primary goal of the proposed methodology is to ensure maximum productivity at minimal cost. Implementation of this methodology will enable more accurate equipment lifecycle forecasting, reduce the risk of ineffective investments, optimize the timing and sequence of automated system implementation, continuously monitor the effectiveness of these innovations, and ensure maximum productivity at minimal cost. The developed methodology was tested at four enterprises, reducing the average development and implementation cycle time for a process line. Before implementing these innovative technologies, the time spent developing, testing, and debugging equipment prototypes accounted for 60%. Pilot prototypes now account for approximately 34% of the time. Pilot production launches have been reduced to 26%. The research also identified factors that negatively impact the implementation of innovations in agricultural activities, including low standardization, delays between the development and implementation of these technologies, and relatively complex approval procedures for new equipment technologies, including environmental certification, quality control, and so on. The selection of production sites for testing and pilot production is also relatively limited. Furthermore, administrative barriers have been reduced. The data obtained provide the basis for developing industry-specific resource efficiency standards and integrating environmental indicators (emissions, waste, and energy intensity) into the ESG monitoring system for agricultural enterprises. This facilitates the comprehensive integration of economic, environmental, and social objectives, supporting the sustainable development of the agricultural sector and improving the quality of life in rural areas.

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