Available online at www.ijournalse.org

Emerging Science Journal

(ISSN: 2610-9182)

Vol. 9, No. 5, October, 2025

New Development Model of the Agro-Industrial Complex Under Green Economy Conditions

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Abstract

This study empirically examines opportunities and provides a conceptual rationale for developing a green economy model tailored to Kazakhstan's agro-industrial complex (AIC). The research focuses on identifying effective strategies for sustainable agricultural development by combining environmental and economic approaches. The methodological basis includes the analysis of theoretical concepts in economic and mathematical modeling, identification of key factors influencing the sector, and the construction of a block structure to represent these factors. Forecasting models were developed to evaluate the efficiency of various strategic directions for transitioning to sustainable agriculture. The findings indicate that the most influential drivers of sustainable development include the expansion of green financial instruments, increased public and international investment, and the use of digital technologies for collecting and processing data. The forecast of key indicators of the green economy in Kazakhstan up to 2030 confirms the reliability and applicability of the proposed evaluation method. The main contribution of this research is the creation of an integrated model that connects theoretical frameworks with practical tools for managing ecological and economic performance in agriculture. The results can be applied in strategic planning, decision-making for the AIC, and academic programs focused on the green economy and sustainable development in Kazakhstan.

Keywords:

Agro-industrial Complex (AIC);
Innovative Development;
Development Model;
Factors;
Green Economy.

Article History:

Received:	27	May	2025
Revised:	17	August	2025
Accepted:	05	September	2025
Published:	01	October	2025

1- Introduction

In the 21st century, humanity has faced new global challenges, such as the depletion of natural resources, threats to global food security, and energy security. Consequently, the world requires a new development model. This model was adopted at the 40th World Economic Forum in Davos in 2010 under the motto "Improve the State of the World: Rethink, Redesign, Rebuild." A new global course toward a green economy is the only way forward [1]. Nevertheless, owing to various internal and external factors, each country has unique smart, resource-efficient, circular, and green living. As an engaged member of the international community, Kazakhstan has endorsed a strategic shift toward a sustainable economic model and is actively pursuing viable pathways to facilitate this transition [2]. Green transition is a reality at the macro-and microeconomic levels and is of great interest in reducing the risks of global threats such as climate change, mineral depletion, and water scarcity. A green economy promotes economic progress, ensures gross domestic product growth, increases a country's income and job creation, and reduces unemployment [3]. In particular, the United Nations

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DOI: http://dx.doi.org/10.28991/ESJ-2025-09-05-019

(UN) was the first to introduce a specific environmental program (UNEP) that interprets the green economy as a resource-efficient economy based on low-carbon development, leading to increased social welfare and equity while significantly reducing environmental risks and preventing biodiversity loss [4].

While the highest academic circles in European Union (EU) countries realized the acute importance of the green agenda and laid the theoretical foundations for the transition to a green economy, Kazakhstan was still an industrial periphery of the Soviet Union. It took Kazakhstan more than 30 years to realize the importance and necessity of actions to change the economy and the national way of thinking in favor of sustainable development [5]. The principles of a green economy are derived from the concept of sustainable development, which today is almost the primary reference point for human development in the foreseeable future because of the clear quintessence of the 17 UN Sustainable Development Goals (SDGs) [6].

The main strategic document of Kazakhstan on the transition to a green economy, the Concept of Transition to a Green Economy, was updated on June 10, 2024, to achieve Kazakhstan's commitment to reducing greenhouse gas emissions under the Paris Agreement while ensuring economic and environmental sustainability, a just and prosperous society, and a clean and healthy environment [7]. In the revised version of the document, as well as in other strategic national documents such as the "Strategy of Kazakhstan-2050", efforts have been made to establish green indicators for the country's economic sectors, identify key problematic factors hindering sustainable development, and propose primary directions for addressing these issues.

However, it is necessary to clearly emphasize the steps in the transition of the agro-industrial complex (AIC) to a green economy. Moreover, in defining quantitative indicators of green growth, it is preferable to rely on econometric calculations and forecasting analysis, which the authors propose within the scope of this study. Emerging studies have emphasized a potential approach to addressing the challenges of transitioning Kazakhstan's agricultural sector toward sustainable development through the systematization of socioeconomic mechanisms as part of strategic management frameworks. The authors argue that there is a need to incorporate risk-mitigation mechanisms into the existing concept for the transition to a green economy [8]. Thus, most domestic researchers agree that only comprehensive, multi-pronged efforts to improve all processes related in one way or another to the agricultural sector will yield tangible results, namely a real transition to a green economy.

All changes in the transition to sustainable functioning require structuring and strategic planning in order to avoid unnecessary and inefficient costs. In other words, the lack of strategic planning for changes in the transition to a sustainable green economy entails irrational and ineffective use of resources and additional costs. The authors believe that this is the main problem encountered when implementing the principles of a green economy in industries, including agriculture. The need for a comprehensive study of this problem and other less extensive studies related to setting clear directions and outlining steps to implement effective measures for AIC transition to a green economy is an urgent issue today.

In addition, a range of systemic problems hinders the development of Kazakhstan's agrarian sector.

- Lack of a holistic approach to the development of domestic AIC.
- Weak development of rural co-operation occurs because agricultural products are sold mainly in the form of raw materials.
- Inefficiency of the state-support instruments.
- The remoteness of agricultural science from business.
- Underdevelopment of agricultural product distribution and storage systems.

Here, the importance of state support is evident for beginner farmers and large companies during the transition to the principles of a green economy in their daily activities, and for companies already producing organic products. They need further greening of the entire production cycle or other assistance to improve their business processes. Kazakhstan has a minimal market for organic food. Most organic products are imported into the country and are usually several times more expensive than locally produced products. Foreigners or locals with upper-middle incomes typically consume them. In addition, there are specific difficulties in exporting organic food produced in Kazakhstan.

Local scientists consider the transition to organic farming integrated with traditional, resource-saving, and combined methods as the primary solution for the accelerated transition to a qualitatively new level of development in the national economy, which certainly includes the agricultural sector [9]. At the same time, without the digital modernization of the agro-industrial complex, it is difficult to achieve competitiveness and profitability in agricultural businesses [10]. In this regard, when undertaking green transition, it is important to consider the value of the industry as the core of food security in the country and to prevent a decline in production volumes or other consequences of a radical change in existing processes. It should be noted that most studies on related topics only provide a general analysis of trends in Kazakhstan's agricultural statistics and mainly focus on individual ways to improve the functioning of the agro-industrial complex: support for agricultural cooperatives, digitization of agricultural processes, reuse of agricultural waste, combating soil degradation and pollution, and water management.

The authors believe that it is not sufficient to change the fundamental patterns of economic activity to separate growth from environmental degradation and support the expansion of commercial eco-agriculture in Kazakhstan. Although the ecological damage from agriculture in Kazakhstan is incomparably less than that from the sectors of economy with more polluting tendencies, there is still a global trend toward improving the environmental friendliness of agriculture, particularly considering that more than 65% of the land in Kazakhstan is agricultural [11]. Support for energy-saving technologies is insufficient owing to a lack of funding, and modern waste management methods and greenhouse gas emission reduction are inefficient and often subject to administrative pressure.

To address these gaps, this study focuses on the results of an econometric and predictive model with carefully selected factor indicators, which increases the accuracy of the directions chosen for concentrating efforts and forecasts the success of implementing recommendations. To create a sustainable agricultural sector, the country is undertaking a multilateral approach that includes technological advances, policy reforms, and the development of public-private partnerships [12]. The main challenges faced by the AIC include land degradation, limited water resources, low energy efficiency of agricultural production, and insufficient adoption of environmentally friendly and resource-saving technologies. Under climate change and increased competition in global food markets, these challenges require urgent measures and a comprehensive approach to sector modernization. The research problem arises from the necessity to examine the influence of green economy factors on the development of the agro-industrial complex (AIC), with a specific focus on the gross output of agriculture, forestry, and fisheries in Kazakhstan, along with other relevant indicators.

International organizations and development banks, such as the Food and Agriculture Organization (FAO) UN, Organization for Economic Co-operation and Development (OECD), European Community (EC), and Asia Development Bank (ADB), are actively cooperating with Kazakhstan and other countries in the region to provide technical and advisory assistance for programs aimed at supporting green agricultural projects. Furthermore, support is being provided to the Kazakh scientific community for conducting research in the field of agriculture. The results of such co-operation are often limited in scope and do not cause major changes to the current situation.

Despite this, the global community recognizes that developing countries are heavily dependent on fossil fuels and thus make a significant negative contribution to environmental pollution. Therefore, countries have joined forces in regional initiatives and programs with the intention of working together to achieve development goals. For example, China's Belt and Road Initiative, which includes Kazakhstan, is an important conduit for green technologies between countries participating in the initiative. China has made significant progress in reducing carbon emissions and introducing green principles into its economy [13].

Therefore, taking into account the results of previous studies, gaps in existing strategic documents concerning the implementation of a green economy in Kazakhstan's agro-industrial complex, and international co-operation in this area, the authors formulated questions that this study aims to answer.

The originality of this research is demonstrated through the following:

- A substantiated rationale for pursuing sustainable development within the economy, with a particular emphasis on the agricultural sector.
- A comprehensive evaluation of the current condition of Kazakhstan's agro-industrial complex (AIC) and its preparedness for adopting a green economy framework.
- The development of a conceptual model for the progression of AIC in Kazakhstan is accompanied by strategic recommendations to facilitate its transition toward sustainability.

This study aimed to develop evidence-based recommendations and proposals to introduce a green economy model into the AIC of Kazakhstan. To address the above complex problems in the existing model of the transition to a green economy, this study analyzed the key factors (presented in the form of a block structure) affecting the dynamics of sector development and developed forecast models to assess the effectiveness of the selected indicators.

This study is relevant because of the need to improve the competitiveness of Kazakhstan's agro-industrial sector through its integration into the international processes of sustainable development, attracting investment in green technologies, optimizing the use of natural resources, and minimizing environmental damage. Particular attention is paid to implementing digital technologies in data collection and analysis, which will increase the transparency and efficiency of the state regulation of agrarian enterprises' production in a green economy.

The novelty of this study includes the following:

- Justification of the need for sustainable economic development, including the agricultural sector.
- Analysis of the current state of the AIC in Kazakhstan and its readiness for transition to a green economy.
- A model for AIC development in Kazakhstan and recommendations for its transition to a green economy.

Considering the initial stage of Kazakhstan's transition to a green economy, especially in the agricultural sector, and the lack of a sufficient model and forecast results for the development of this transition in the coming years, the proposed model for AIC development in Kazakhstan in the transition to a green economy and the given recommendations are of scientific and practical importance for stakeholders and the Kazakhstan scientific community.

This study aims to form a scientific and practical basis for government agencies, businesses, and international organizations interested in the development of sustainable agriculture. To this end, the authors analyzed scientific research by foreign and domestic scientists on the sustainability of the agricultural sector.

To summarize the sections of this study, Section 2 reviews the current foreign and domestic scientific literature on the latest findings and results of the implementation of green economy principles and transition to sustainable agriculture, as well as the impact of such a transition on the economic climate. Section 3 presents the theoretical and methodological foundations of this study, including a detailed description of the materials, methods, and stages. Section 4 presents the elaborated calculations and their outcomes analysis. Section 5 performs a comparison between the study's research model efficiency and previous works in the same area, approbating and verifying the results of this study. Section 6 summarizes the achievements and contributions of this study, also specifying study limitations and future study perspectives.

2- Literature Review

Global scientific literature presents many studies on the green economy, while agricultural science in Kazakhstan is experiencing a substantial climb. However, the implementation of the proposed research results in a green economy in the real sector of the country that carries an exclusively point-like character and does not represent tangible changes.

When discussing modern scientific works on the introduction of the principles of sustainable agriculture and green economy in agricultural production, it is necessary to emphasize the Indian scientific community. For example, Ajatasatru et al. [14] proved the general economic effect of sustainable development on crop production. They offer efficient recommendations to Indian government officials and policymakers to adjust existing policies and measures to improve the agricultural sector. Consequently, in the livestock sector, an increasing number of farmers and farmer cooperatives worldwide, concerned about the continual use of antibiotics in their practices, have transitioned to closed-process livestock farms and biological breeding methods to produce environmentally friendly and safe meat products. In addition, research has shown the possibility of ensuring food security through the sustainable integration of the entire breeding process of large and small livestock, from gene control to nutrition, and the organization of a waste-free production process [15].

Transdisciplinary topics at the intersection of economics and ecology in the agricultural sector are in the spotlight. Chinese scientists have processed data from several regions and identified an economic relationship between agricultural expansion and cropland degradation combined with irrigation water scarcity [16]. In these countries, there is already a clear public and political understanding of the role of environmental protection and sustainable development of all major sectors of the economy, including the agro-industrial complex, and the research results of scientists are actively implemented in the real sectors of production.

Another extensive study of 24 EU countries in 2021 found that the harmonized consumer food price index had the most significant influence on the food security index in 2021, whereas the impact of median equivalent net income and moderate or severe food insecurity was minimal [17]. While existing research provides valuable insights into the application of green technologies in agriculture, there remains a need for further exploration of their roles in crop and livestock production, particularly in relation to food security and broader macroeconomic outcomes. The wider integration of green economy principles is particularly evident in European Union member states. For instance, countries such as France and Germany have made significant progress in advancing green technologies within the agricultural sector and actively supported the expansion of organic farming practices. These countries have already achieved a significant share of ecologically certified land and organic farms and active use of renewable energy sources in the AIC [18]. However, approaches to the green economy in AIC, researched and presented by the aforementioned scientists, are not fully applicable to Kazakhstan because of regional geographical, political, and economic specifics.

A more recent study on the impact of emissions on the food systems in European countries, covering the period from 2010 to 2024, showed increasing hydrocarbon emissions in the food processing industry and persistently high levels of agricultural emissions in regions that use fossil fuels. One of the main measures proposed in this study to remedy this situation is the introduction of regionally oriented sustainable development strategies and comprehensive measures to modernize infrastructure and control. These measures are also applicable to Kazakhstan given the heterogeneity of regions within the country [19].

Domestic scientists analyzed an impressive list of external and internal obstacles hindering the sustainable development of the agro-industrial complex of Kazakhstan [20]. In the scientific community of Kazakhstan, the hopes for the prospects of green economy development in the studied sectors of the agro-industrial complex are quite high. It is expected that the vector of the state's economic policy will shift toward the transition to a green economy in the AIC. When organic agricultural production is developing, state support for commercial farming units and farmers initiating the implementation of the green agenda is increasing, and the results of the ongoing import substitution for agricultural products are visible [21, 22]. The authors of this study support the position of Lukpanova et al. [23], who argued that environmental problems caused by the current development of AIC cause significant ecological damage. Optimizing and structuring financial flows to support environmentally friendly innovations and solutions is evidence in favor of the sustainable development of AIC [24].

The digitalization of Kazakhstan's energy and agro-industrial complexes is worth mentioning. Thus, Saparova et al. [21] believes that, given the low level of relevant infrastructure across the country for the active introduction of digital technologies, insufficient investments, low level of mechanization, and other factors, it is necessary to make a gradual and less expensive transition. For example, introducing electronic decision support tools to smartphone-based farms could be a starting point for the development of large-scale digitalization of agriculture in the country [21]. Smagulova et al. [24] analyzed the potential of digital technologies to improve the efficiency and sustainability of the most essential sectors of the country's economy, including agriculture, and revealed a positive effect of their introduction into production processes [24]. Because of attempts to explore various factors and directions influencing AIC development in the transition to a green economy, the authors identified four primary sources of this influence. These indicators were selected using a method for analyzing the direct and indirect influences on the achievement of the UN SDGs and the country's agricultural sector. The indicators were monitored using official OECD country data and official statistics from Kazakhstan. Each of them, collectively and individually, is supported by monitored indicators and has the potential to influence the course of ongoing changes in the agricultural sector toward sustainability.

One of the primary anticipated outcomes of Kazakhstan's transition to a green economy is its positive influence on key sociological and economic indicators. These include ensuring national food security, enhancing household income levels, and generating new employment opportunities that are both safer and more sustainable, thereby reducing the overall unemployment rate. It is possible to consider the first block (Block 1) to identify the indicators of impact on the green economy. Owing to deteriorating climatic conditions, increasing frequency of natural disasters, and shortage of non-renewable energy sources, there is a tendency among farmers and large agricultural producers in Kazakhstan to increase their interest in new technologies for saving water resources, partial utilization of wind and solar energy, and increasing the share of zero-waste production. Kazakhstan's vast renewable energy potential, especially for solar and wind energy, is a key strategic asset for addressing the challenges faced by the agricultural sector.

Second, the environmental component of all initiatives and pollution control should become the second block (Block 2), and the solution to its problems should be a priority for the development of strategies and models. Investment in environmental protection, biodiversity preservation, and the transition to a green economy plays a significant role in shaping the institutional environment, advancing scientific capacity, and enhancing the qualifications of research personnel. However, environmental initiatives, including those related to agriculture, often face financial constraints [25]. According to World Bank data, in 2021 and 2022, the member states of the Eurasian Economic Union (EAEU), including Kazakhstan, collectively allocated less than 2% of their GDP to R&D activities [26].

Third, the aforementioned data on the lack of an effective link between science, education, and actual implementation in agricultural processes created the third block (Block 3). Kazakhstan's successful transition to a green economy depends significantly on an adequate, strategically verified level of investment and public financing in creating new green projects and industries and transforming existing ones.

Fourth, farm viability depends on investment to ensure future food production. To meet the growing production demands of developing nations, it is essential to significantly scale up investment. This includes a projected 50 percent rise in private sector funding directed toward primary agricultural production and processing activities, alongside substantial public investment in critical infrastructure, such as transportation networks, irrigation systems, energy supply, and educational services. Thus, we define investment in a green economy as the fourth block (Block 4).

Recent scientific studies have confirmed the need for strategic investments in advanced technologies, targeted programs to improve employee knowledge, and an appropriate advanced regulatory framework for the transition to sustainable production systems has been confirmed by recent scientific studies [27]. Having carefully studied the aforementioned scientific literature, the authors conclude that there is a need for more in-depth research on the prospects of green economic development in the AIC of Kazakhstan, given the existing regulatory and legal framework. In addition, recommendations based on this study would be helpful to stakeholders for further consideration in their work, using the principles of the green economy.

3- Data and Methodology

The authors critically examined existing regulatory documents in force in Kazakhstan for their completeness and readiness to provide a methodology for implementing the green economy as a theoretical basis for this study.

3-1- Research Materials

Critical analysis of the Concept of Transition of the Republic of Kazakhstan to a "green economy," updated in 2024, which reflects the main directions and specific target indicators up to 2060, as the primary document obliged to provide clear directions to ensure a transparent process of transition of the existing economy to a green economy revealed certain shortcomings [7]. This strategic state document lacks a plan for the transition of each sector of the economy to a green one. The descriptive section, analysis, and conclusions are superficial and do not contain clear steps and methods to achieve sustainable green growth. However, according to the authors, for a more effective transition of each economic sector to green principles, the relevant document should be adopted separately for each sector. For example, from the perspective of AIC, the Concept lacks the specific mechanisms and activities to achieve the sustainability indicators specified in the document. In addition, this study relies on the core statistical macroeconomic indicators of Kazakhstan and green economy indicators worldwide and in Kazakhstan. We also emphasize the problem of data availability and reliability when analyzing the transition to a green economy in Kazakhstan.

3-1-1- Factor Analysis of the Econometric Model

Here, we provide a rationale for selecting the factors in the econometric model of green economic development (Table 1), ensuring that it captures the multidisciplinary essence of this phenomenon by incorporating the social, economic, environmental, scientific, and innovative dimensions. Therefore, the factors were grouped into four semantic blocks, each of which played a determining role in sustainable development.

Table 1. Factors of the econometric model of green economic development

No.	Variable	Justification
Block 1: Socioeconomic Sphere		
X_1	Volume of production of the agro-forestry-fishery industry	The agricultural sector is very vulnerable to climate change and resource sustainability. Its growth reflects the effectiveness of the green approaches.
X_2	Volume of environmentally friendly production	Direct indicator of adopting green technologies and demand for sustainable products.
X_3	Share of the population with income below the subsistence minimum	It indicates social sustainability, which is critical for assessing the equity of green growth.
Block 2: Environmental Sphere		
X_4	Greenhouse gas emissions (including land use)	The principal metric of environmental impact serves as a measure of the extent to which human activities affect natural ecosystems.
X_5	CO_2-emissions	The primary constituent of greenhouse gas emissions has the most significant impact on climate change.
X_6	Number of approved environmental impact assessment (EIA) projects	The indicator of environmental expertise and compliance with sustainable development standards.
X_7	Environmental protection costs	An economic indicator demonstrating efforts to reduce negative environmental impacts.
Block 3: Science and Education		
X_8	The number of scientific publications in the environmental sphere	The number of scientific publications in the environmental sphere reflects the intellectual contribution to the development of sustainable environmental practices and contributes to the formation of informed decisions in environmental protection.
Block 4: Investment in the Green Economy		
X_9	Investments in environmental protection	Investments in environmental protection directly affect the implementation of environmentally oriented initiatives and contribute to the effective implementation of sustainable development strategies.

A sustainable and effective model of a green economy requires a comprehensive and balanced approach that considers the interdisciplinary nature of the phenomenon. Accordingly, the econometric model is structured around a justified classification of variables into four principal thematic categories: socioeconomic factors, environmental parameters, elements related to science and education, and investment in environmental protection initiatives. This approach provides a comprehensive reflection of the processes that affect sustainable development.

When selecting factors, various possible indicators potentially characterizing the state and dynamics of the green economy were analyzed: the index of environmental efficiency, the level of waste recycling, the share of renewable energy sources (RES) in the energy balance, the index of environmental regulation, coverage by environmental education, and others. However, these were excluded from the comparative analysis for the following reasons: fragmented statistical information, significant gaps in the dynamic series, lack of comparability of data across regions, and less pronounced dependence on the target parameters of sustainable growth.

As a result of detailed selection and peer review, nine key variables were identified, each meeting the following criteria:

- Availability and reliability of the statistical data;
- Availability of the dynamics and measurability;
- Meaningful relevance of the concept of a green economy.

Consequently, the set of selected variables constitutes a coherent and well-structured foundation for modeling the dynamics of sustainable development within the framework of a green economy. The configuration of these indicators ensures both methodological rigor and practical relevance of the econometric model, making it suitable for monitoring, evaluating, and forecasting the outcomes of implemented environmental and socioeconomic policies.

When building an econometric model of green economy development, it is critical to choose a representative and sufficiently long time series that makes it possible to identify stable relationships between variables. In this case, the period from 2015 to 2022 was the basis of the analysis because of the following substantive and methodological considerations.

- *Availability and completeness of official statistics*. Since 2015, most indicators reflecting the environment, investment, production, and development of the green economy have been systematically reflected in statistical compilations in an agreed and unified form. Data from previous years often have fragmentary characteristics, differ methodologically, or are unavailable, making their use in modeling complicated.
- *The current stage of development of the environmental agenda*. The period starting in 2015 corresponds to the activation of the international and national environmental agendas. This year, the UN Sustainable Development Goals (SDGs) were adopted, and the Paris Climate Agreement was signed, which gave impetus to a systematic approach to the green economy in many countries, including at the national level.
- *Methodological comparison of the data*. The selected period provided a unified methodological basis for calculating the variables. Since 2015, statistical approaches have been harmonized at the interagency level, making the data internally consistent and suitable for quantitative analysis.
- *Sufficient length of the series*. Eight years is the optimal ratio between length and data quality for building an econometric model. Smaller intervals do not provide statistical stability to the results, and lengthening the series owing to earlier years may entail distortions because of the lack of comparability.
- *Objective limitations of the sources*. Statistical compilations, the primary data sources, provide a stable and continuous set of information, starting in 2015, owing to the updating of classifiers, the introduction of digital data collection and processing systems, and the transition to more transparent reporting forms.

Considering the considerations outlined above, the selection of the 2015-2022 timeframe appears to be methodologically sound, empirically grounded, and practically well-justified. This period offers a robust empirical foundation for constructing a reliable and sustainable econometric framework for analyzing green economic development. The development of a green economy forecast requires consideration of multiple interrelated factors covering socioeconomic, environmental, scientific, and investment aspects. Given the multifactorial nature of the problem under study, an econometric model was used in this study in the form of a system of simultaneous (joint) equations that allows:

- Simultaneously, we consider the influence of interdependent variables (endogenous factors), which are important for complex analysis.
- It distinguishes between exogenous and endogenous factors, thereby clarifying cause-and-effect relationships in the system.
- Model's reverse and cross effects between sectors (e.g., the impact of emissions on the economy and vice versa).

The model consists of several equations, each of which describes a separate process or component of the sustainable development system. Endogenous variables (e.g., Y_1- a conditional integral indicator of sustainable development) are explained by a set of exogenous variables (X_1, X_2, ..., X_8) characterizing the essential indicators in agriculture, environment, science, and investment.

The forecast stages were as follows:

- Estimation of model coefficients based on historical data for 2015-2022;
- Calculation of the forecast values of the endogenous variables (e.g., Y_1×(T+1), Y_1×(T+2)) using extrapolation and substitution in equations;
- The sensitivity analysis made it possible to assess the robustness of the model to changes in the input data and to consider possible forecast errors.

- The choice of exogenous variables was based on the representativeness, significance, and availability of statistical data as well as their role in the formation of sustainable development.
- The preparation of scenario analysis as a groundwork for future studies with the possibility of modeling alternative development trajectories considering global and regional shocks.

It is impossible to adequately describe the multilevel nature of the green economy using a single regression equation, because a system reflecting the interrelationships between sectors and spheres is necessary. Simultaneous equations make it possible to consider complex interactions between factors, including closed loops of influence. The availability of reliable data for 2015-2022 makes it possible to qualitatively identify the model and obtain stable estimates. The structural model is suitable for extrapolation and scenario analysis, as a convenient tool for forecasting and planning.

Alternative approaches, such as one-dimensional regression models, have also been considered. However, one-dimensional models do not reflect the mutual influence of variables, which reduces the interpretability of the results and is undesirable for an applied analysis in the context of sustainable development policies. Consequently, the choice of a system of simultaneous equations is justified theoretically and empirically. This made it possible to consider the specifics of the green economy as a complex and interdependent phenomenon subject to internal and external influences.

Let us indicate the main economic and environmental factors selected according to the criterion of data availability, and correlate them with the four main blocks of factors described earlier, which will help build further research. Table 2 provides a description of the factors considered in this study.

Table 2. The primary factor indicators of statistics characterizing the dynamics of green economy development in Kazakhstan for 2015-2022

Factors	2015	2016	2017	2018	2019	2020	2021	2022
Environmental protection investments, million tenge	32.526	43.937	86.962	111.161	198.722	173.619	171.165	159.661
Greenhouse gas emissions, land use and forestry, million tons/year	32.05	27.42	25.21	20.67	14.37	8.13	2.71	2.65
Greenhouse gas emissions, carbon dioxide, million tons/year	345.8	282.3	318.2	327.7	289.5	263.5	257.7	261.9
Number of approved EIA projects, pcs	2.565	2.909	3.514	3.402	1.174	800	107	376
Number of publications in the area of environment, pcs	367	441	220	220	12.363	13.829	13.192	6.155
Environmentally friendly production, million tenge	8.653	12.754	51.634	60.866	52.674	57.987	58.329	91.322
Agriculture, forestry and fishery product (service) gross output at current prices, million tenge	3229.52	3701.42	4092.33	4497.59	5177.89	6363.98	7549.83	9521.02
Total environmental protection costs, million tenge	154.810	196.143	262.407	302.177	420.392	384.016	416.956	444.514
Share of the rural population with incomes used for consumption below the subsistence minimum, %	3.9	4.2	4.6	6.7	6.6	7.6	7.2	7.3

Source: Compiled by the authors based on data from the Statistics Agency of the Republic of Kazakhstan [28] and the Organization for Economic Co-operation and Development (OECD) [29].

Given the aforementioned data, modeling the dynamics of the development of the factorial feature of the green economy requires considering the breadth of the economic base. Expressing the "integrity effect" of an economic system requires combining the indicators under study into separate aggregates or blocks. Each block of indicators reflects the dynamics of a component of an economy.

The representation of the block structure expressing the model with its internal links between indicators is formed by the equations of the econometric model of statistical analysis of the mutual influence of green economy factors on the gross products of agriculture, forestry, and fishery. The econometric model is a set of regression equations that expresses heterogeneous environmental and economic indicators or variables.

The system of simultaneous equations under study assumes that the endogenous variables (y_1 , y_2 , ..., y_G) depend on the exogenous variables (x_1 , x_2 , ..., x_K), making it possible to build a structural model with several equations. Each equation in the system includes the relationship between the corresponding variables, whereas variable Y_G is excluded from each g-equation, which avoids multicollinearity and improves the accuracy of the estimates. Forecasts were built in steps, starting with the calculation of b_{Gi} and C_{Gi} coefficients for each year in the model, to make it possible to accurately account for the changes and trends observed in the data. Forecasting involves several steps: The first step involves calculating all necessary model coefficients. The second step involved calculating the forecast values for each year (T+1, T+2, etc.), which allowed us to obtain the dynamics of the changes in the variables under study over the long term. Extrapolation based on the data above was used to forecast each year. In the third step, the values of the forecast variables were obtained, for example, for $Y_1 \times (T+1)$, $Y_1 \times (T+2)$, etc.

The data used for the analysis included a set of variables characterizing various aspects of the green economy of the Republic of Kazakhstan. These variables include indicators of agriculture, cleaner production, greenhouse gas emissions, environmental protection costs, and other key indicators that can influence the dynamics of economic change. Each variable in the system of simultaneous equations plays a different role in modeling the economic processes that affect the development of the green economy. The choice of data relies on the source reliability and the time interval of the analysis to obtain more accurate and representative results. Specifically, for all factors in Table 2, data for the following categories were used:

- ***Socioeconomic sphere***: gross output of agriculture, forestry, and fishery production, the share of the rural population with incomes below the subsistence level
- ***Environmental sphere***: greenhouse gas emissions, environmental protection costs, and number of approved environmental impact assessment projects
- ***Science and education***: Number of publications in the area of the environment.

Forecasting uses exogenous variables (X_1, X_2, ..., X_8), which make it possible to consider the influence of external factors on the dynamics of green economy development. Additionally, to assess the reliability of the results, sensitivity analysis methods were used to test the robustness of the model to changes in input data and assumptions. This also improved the overall reliability of the forecast values obtained.

A key direction for future research is to consider external shocks and changes in the global economic environment. For example, fluctuations in energy prices, climate change, and international initiatives to reduce greenhouse gas emissions can significantly affect the effectiveness of the proposed model. Therefore, in the future, a scenario analysis will be necessary to consider the various macroeconomic and environmental factors that affect the projected indicators. Under these conditions, econometric models in the form of a system of simultaneous (joint) equations are preferred according to the method below.

3-1-2- Materials for the Predictive Model

In this context, the use of econometric models represented as systems of simultaneous equations is considered the most appropriate methodological approach, as outlined in the method described below [30]. Suppose a system of joint simultaneous equations (structural model) is given, where $Y_1, Y_2, ..., Y_g$ are endogenous variables and $X_1, X_2, ..., X_K$ are exogenous variables.

$$\begin{cases} Y_1 = b_{10} + b_{12}Y_2 + b_{13}Y_3 + \ldots + b_{1G}Y_G + C_{11}X_1 + C_{12}X_2 + \ldots + C_{1K}X_K + \varepsilon_1 \\ Y_2 = b_{20} + b_{21}Y_1 + b_{23}Y_3 + \ldots + b_{2G}Y_G + C_{21}X_1 + C_{22}X_2 + \ldots + C_{2K}X_K + \varepsilon_2 \\ \ldots \\ Y_G = b_{G0} + b_{G2}Y_2 + \ldots + b_{G-1,G-1}Y_{G-1} + C_{G1}X_1 + C_{G2}X_2 + \ldots + C_{GK}X_K + \varepsilon_G \end{cases} \tag{1}$$

$$\begin{cases} Y_g = b_{g0} + \sum_{i=1}^{G} b_{gi}Y_g + \sum_{j=1}^{K} C_{gj}X_j \\ g = 1,2,\ldots,G \end{cases} \tag{2}$$

Variable Y_G is not included in each g-equation.

The researchers used the following notations when calculating the confidence interval:

where N is the total number of observations in the sample; for example, if a dataset is analyzed, N is the number of all data points used to calculate the confidence interval.

where K is the number of degrees of freedom, which is often used in t-distribution for a sample of N observations, G is the sample or population mean.

The algorithm for implementing the forecast calculations is as follows:

Step 1. Let us assume that system (1) is found for each year (moment) of time, that is, the calculation of coefficients b_{Gi} and C_{Gi}.

Step 2. Let us determine the forecast values $Y_g^*(l+T)$ and $X_j^*(l+T)$ using a method for forecasting the dynamic series.

Step 3. Let us determine the forecast values of the endogenous variables.

After performing step 3, the following is obtained.

Let us determine the forecast value of $\hat{Y}_1^*(T+1)$.

$$\begin{cases} \hat{Y}_1^*(T+1) = b_{10} + b_{12}Y_2(T+1) + b_{13}Y_3(T+1) + \cdots + b_{1G}Y_G(T+1) + C_{11}X_1^*(T+1) + C_{12}X_2^*(T+1) + \cdots + C_{1K}X_K^*(T+1) \\ \hat{Y}_2^*(T+1) = b_{20}(T+1) + b_{21}\hat{Y}_1(T+1) + \cdots + b_{2G}Y_G(T+1) + \cdots + C_{21}X_1^*(T+1) + \cdots + C_{2K}X_K^*(T+1) \\ \hat{Y}_3^*(T+1) = b_{30}(T+1) + b_{31}\hat{Y}_1^*(T+1) + b_{32}\hat{Y}_2^*(T+1) + \cdots + b_{3G}Y_G^*(T+1) \\ \ldots \\ \hat{Y}_G^*(T+1) = b_{G0}(T+1) + b_{G1}\hat{Y}_1^*(T+1) + b_{G2}\hat{Y}_2^*(T+1) + \cdots + b_{G-1,G-1}Y_{G-1}^*(T+1) \end{cases} \tag{3}$$

and the like at $T + 2, T + 3, \ldots, T + L$.

Step 4. Calculating the confidence interval:

$$\Delta Y_g^*(T+l) = \pm t_{\alpha,N-(G-1)-K-1} \cdot \sigma_{\varepsilon_t}(g) \tag{4}$$

To build the forecast model in Table 3 further, the factors presented in the previous table were distributed directly into the blocks.

Table 3. Symbols of the main statistical indicators characterizing the dynamics of green economy development in the Republic of Kazakhstan

No.	Notation	Factors	Unit of measure
Block 1. Socioeconomic sphere			
1	X_1	Agriculture, forestry and fishery product (service) gross output at current prices	Million tenge
2	X_2	Environmentally friendly production	Million tenge
3	X_3	Share of the rural population with incomes used for consumption below the subsistence minimum	%
Block 2. Environmental sphere			
4	X_4	Greenhouse gas emissions, land use and forestry	Million tons/year
5	X_5	Greenhouse gas emissions, carbon dioxide	Million tons/year
6	X_6	Number of approved environmental impact assessment (EIA) projects	Units
7	X_7	Total environmental protection costs	Million tenge
Block 3. Science and education			
8	X_8	Number of publications in the area of environment	Units
Block 4. Investment in the green economy			
9	X_9	Environmental protection investments	Million tenge

The variables are distributed by blocks as follows:

- The socioeconomic block includes indicators reflecting production in environmentally sensitive sectors (agro-forestry-fisheries), share of environmentally oriented production, and poverty rate as an indicator of social sustainability. These parameters reflect the fundamental relationship between social equity, sustainability of the productive sector, and green development.
- The environmental block is based on indicators of the actual environmental impact (greenhouse gas and carbon emissions), degree of environmental regulation (environmental impact assessment (EIA) projects), and financial investments in environmental protection. This block makes it possible to assess the level of environmental load and the efforts to reduce it.
- Scientific and educational blocks are represented by the number of scientific publications on environmental topics as an indicator of the generation and transfer of environmental knowledge, which is the intellectual foundation of sustainable solutions.
- The investment block includes direct capital investments in environmental protection, which ensures the implementation of green initiatives.

The distribution of factors into these blocks is not accidental; it allows us to build a step-by-step modular econometric model that reflects the contribution of each component to the overall development of the green economy. Such modularity enables individual analyses within the blocks and further integration into the aggregated model, thereby expanding analytical and forecasting capabilities.

In Table 3, the selected factors received conventional notation for further model building. The authors believe that the formed blocks cover the main components of the economy and allow the modeling of their evolution in dynamics [31].

$$
\begin{aligned}
&\mathrm{X}_1 = a_0 + a_1 \cdot X_2 + a_2 \cdot X_6 + a_2 \cdot X_7 \\
&\mathrm{X}_2 = a_0 + a_1 \cdot X_3 \\
&\mathrm{X}_6 = a_0 + a_1 \cdot X_9 + a_1 \cdot X_8 \\
&\mathrm{X}_7 = a_0 + a_1 \cdot X_4 + a_2 \cdot X_5
\end{aligned}
\tag{5}
$$

3-2- Research Methods

The methodological foundation of this study is based on the application of regression and correlation analyses, which are particularly suitable for modeling multivariate time series. The construction of such models is grounded in systems of regression equations, allowing for a structured representation of the interdependencies among dynamic variables. This approach not only facilitates a rigorous assessment of the strength and direction of the influence exerted by individual explanatory variables on the dependent variable but also enhances the reliability of analytical forecasts and scenario evaluations [32]. During the analysis, the following forecasting methods were used to estimate the dynamic series: the extrapolation method to calculate the forecast values of endogenous variables and other time-series methods such as moving averages and AutoRegressive Integrated Moving Average (ARIMA) models. To assess the reliability of the results, sensitivity analysis methods were used to test the robustness of the model to changes in the initial data and assumptions that improve the overall reliability of the forecast values obtained. These methods were selected from among other existing calculation models because of the presumed reliability of the results and consideration of available factors and variables.

3-3- Research stages

Figure 1 shows the complete research design process as a flowchart, starting from problem formulation and ending with conclusions and pooling for further research.

The development of the methodology is based on the following steps:

Model selection: The econometric model is chosen as a system of simultaneous equations (structural model, form (1)) as the most appropriate to account for interrelations.

Model structure: Definition of a block structure (socioeconomic sphere, ecology, science and education, and investment) for the aggregation of indicators.

Definitions of variables are the following

- Endogenous variables (y_1 , ..., y_G) are the predicted and dependent variables (e.g., gross agricultural output).
- The exogenous variables (x_1 , ..., x_K) are independent external factors (e.g., greenhouse gas emissions, investment, and others) and are labeled as X_1-X_9.

Forecasting algorithm (as part of the methodology): Detail the steps for calculating forecast values.

Validation methods: Selection of sensitivity analysis methods to check the stability of the model.

Data collection and preparation include the following

- Collection of statistical data on selected variables (X1-X9) for a relevant period (e.g., 2015-2022).
- Processing and organizing the data for use in the model.

Figure 1 shows a flowchart of the complete structure of our research process, including all stages of the study.

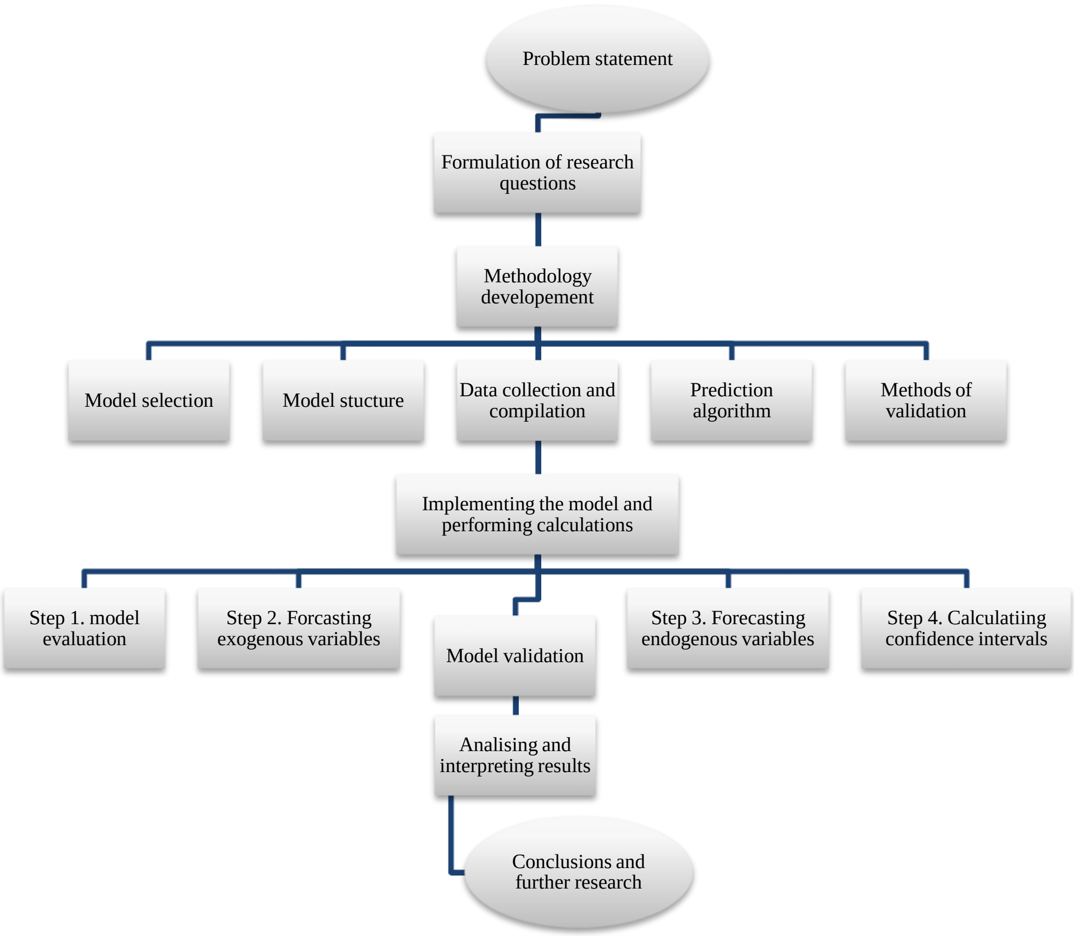

Figure 1. Flowchart of structured information of the research process

The main results of the study are analyzed in Section 4 after validating the model.

4- Results

4-1- Analysis Results and the Forecast Model

A quantitative assessment and forecasting of the selected factor indicators are carried out using the first equation of the multifactor model as an illustrative case. For each year within the LLL observation period, a multifactor regression model was constructed to ensure the elimination of multicollinearity among the explanatory variables and the justification of the model's functional specification. The resulting parameter estimates were expected to be unbiased, consistent, and efficient throughout the analysis period. The linear specification of the model is represented as follows [33]:

$$\hat{Y}_l = a_0x_0 + a_1x_1 + a_2x_2 + \ldots + a_mx_m \tag{6}$$

where Y_l is the modeled indicator of year l, x_i are factors affecting this indicator; I = (0, m), a_i are the model equation coefficients; I = (0, m); and m is the number of factorial features.

The cumulative multiple correlation coefficient r_y reflects the assessment of the characteristics of the obtained regression model. It characterizes the closeness of the relationship between the effective feature Y and the factorial features x_1, x_2, ..., x_m and is generally determined by the following formula:

$$r_y = \sqrt{\frac{\sigma^2_{y12\ldots m}}{\sigma_{x^2}}} = \sqrt{1 - \frac{\sigma^2_{y(12\ldots m)}}{\sigma_{y^2}}} \tag{7}$$

The given form of the index recording is interpreted as follows:

The square of r_y value is the coefficient of multiple determinations that characterizes the proportion of the influence of the selected features on an effective factor:

$$B_y = r_y^2 = \frac{\sigma^2_{y12\ldots m}}{\sigma_{y^2}} \tag{8}$$

We evaluated the first regression equation and defined the vector of regression coefficient estimates. According to the least-squares method, vector $s$is is obtained from the following expression:

$s = (X^TX)^{-1}X^TY$.

The resulting regression equation is as follows:

$Y = -2887382.5171 + 28.2303 \cdot X_1 - 155.5007 \cdot X_2 + 0.02015 \cdot X_3$

The obtained regression equation then checks the significance of the equations and coefficients by studying the absolute and relative approximation errors.

For an unbiased estimate of the variance, we perform the following calculations:

Table 4 shows unbiased error $\varepsilon = Y - Y(x) = Y - X*s$ (absolute approximation error).

Table 4. Statistical analysis of the obtained regression equation Y

Y	Y(x)	ε = Y Y(x)	ε^2	$(Y-Y_m)^2$	|ε : Y|
3701415.4	4213416.205	-512000.805	262144824498.37	4588241112324	0.138
4092333	3311809.09	780523.91	609217574373.77	3066352610880.2	0.191
4497585.4	4391281.222	106304.178	11300578299.414	1811306839104	0.0236
5177893.7	6888720.235	-1710826.535	2926927434206	442943092276.09	0.33
6363976.1	6363816.155	159.945	25582.285	270964702523.29	2.5E-5
7549827.9	7145029.851	404798.049	163861460327.51	2911782189630.3	0.0536

The auxiliary data in Table 4 used for calculating the regression equation indicators were used for further calculations. An example is variance estimation:

s_e^2= (Y-Y(X))T(Y-Y(X)) = 4840289722768.4

The unbiased variance estimate is as follows:

$$s^2 = \frac{1}{n-m-1} \cdot s_e^2 = \frac{1}{5-3-1} \cdot 4840289722768.4 = 1613429907589.5$$

The standard deviation estimate is as follows:

$$S = \sqrt{S^2} = \sqrt{1613429907589.5} = 1270208.608$$

The multiple correlation coefficient can be determined through a matrix of paired correlation coefficients:

$$R = \sqrt{1 - \frac{\Delta_r}{\Delta_{r11}}} \tag{9}$$

Strong link between feature *Y* and factors x_i:

$$R = \sqrt{1 - \frac{0.0214}{0.117}} = 0.9045$$

The obtained calculated value demonstrates a strong relationship between feature *Y* and factor x_i. The coefficient of determination is

$$R^2 = 1 - \frac{s_e^2}{\sum(y_i - y)^2} = 1 - \frac{4840289722768.4}{26616103560985} = 0.8182$$

A statistical test was conducted to determine the significance of the regression equation and evaluate the overall adequacy of the multiple regression model. Specifically, the null hypothesis assumes that the coefficient of determination for the general population is equal to zero, i.e., $R^2 = 0$, or that all regression coefficients ($b_1 = b_2 = ... = b$) are simultaneously insignificant. To test the alternative hypothesis − $H_1 : R^2 \neq 0$ − which posits that at least one of the explanatory variables has a statistically significant influence, the F-statistic based on Fisher's distribution was applied using a one-tailed test approach [34].

If $F < F_{kp} = F_{\alpha}; n - m - 1$, then there is no reason to reject H_0.

$$F = \frac{R^2}{1-R^2} \cdot \frac{n-m-1}{m} = \frac{0.8181}{1-0.8181} \cdot \frac{7-3-1}{3} = 4.499$$

Table value for degrees of freedom $k_1 = 3$ and $k_2 = n–m – 1 = 7 - 3 - 1 = 1$, $F_{kp}(3;3) = 9.2766$

As the actual value of $F < F_{kp}$, the coefficient of determination was deemed not statistically significant.

To check for multicollinearity, the variance inflation factor (*VIF*) was calculated using the following equation.

$$VIF_i = \frac{1}{1-R_i^2}$$

where R_i^2 is the coefficient of determination in regression X_i for all other factors.

To check for multicollinearity, the coefficients of determination R^2 from the auxiliary regressions of each of the explanatory variables on the others were calculated. The following values were obtained: $R_{X2}^2 = 0.6295$, $R_{X6}^2 = 0.7269$, $R_{X7}^2 = 0.789$.

For variable X_2:

$$VIF_{X2} = \frac{1}{1-R_{X2}^2} = \frac{1}{1-0.6295} = \frac{1}{0.3705} = 2.70$$

For variable X_6:

$$VIF_{X6} = \frac{1}{1-R_{X6}^2} = \frac{1}{1-0.7269} = \frac{1}{0.2731} = 3.66$$

For variable X_7:

$$VIF_{X7} = \frac{1}{1-R_{X7}^2} = \frac{1}{1-0{,}789} = \frac{1}{0.211} = 4.73$$

The *VIF* values for all variables were less than five, indicating the absence of serious multicollinearity. Correction of the model to eliminate multicollinearity is not required.

The calculations returned the following multiple regression equation:

$$X_1 = – 2887382.5171 + 28.2303 \cdot X_2 – 155.5007 \cdot X_6 + 0.02015 \cdot X_7$$

This allowed for an economic interpretation of the coefficients of the model. Specifically, a one-unit increase in variable X2 corresponds, on average, to a decrease in X1 by 28.23 units; similarly, a one-unit increase in X6 results in an average reduction of X1 by 155.5 units, while a one-unit rise in X7 is associated with an average decline in X1 of 0.0202 units. Given the maximum absolute value of the coefficient $\beta 3 = –0.451$, the X7 identifies as the most influential factor affecting the dependent variable X1. The statistical validity of the model was confirmed using the coefficient of determination and Fisher's F-test [33], with 81.82% of the total variation in X1 explained by changes in explanatory variables Xj.

Following the presented mathematical forecasting method, based on a dynamic series, forecast calculations were conducted for the remaining primary indicators of statistics, characterizing the dynamics of the development of the green economy in the Republic of Kazakhstan (Table 5).

Table 5. Forecast values of the main statistical indicators characterizing the dynamics of green economy development in the Republic of Kazakhstan for the period between 2023 and 2030

Year	Prediction	Equation characteristics	
X_1. Agriculture, forestry and fishery product (service) gross output at current prices, million tenge			
2024	10529172.90	Model equation: $X_1 = – 2887382{,}5171 + 28{,}2303 \cdot X_2 – 155{,}5007 \cdot X_6 + 0{,}02015\ X_7$	
2025	11466320.80		
2026	12403468.70		
2027	13340616.60		
2028	14277764.50		
2029	15214912.40		
2030	16152060.30		
Quality assessment of the regression model			
Coefficient of determination (R^2)		0.8182	
F-statistics		4.499	
p-value of F-statistics		0.220	
Standard error (S_y)		1270208.608	
The № of observations		8	
The № of explicative variables (X_2, X_6, X_7)		3	
Conclusion: The model explains approximately 81.8% of the variance of the dependent variable, but the p-value for the F-statistics is above 0.05, indicating that the model is statistically insignificant at the 5% level. This may be the result of the small number of observations.			
Checking for multicollinearity Variance Inflation Factor (VIF)			
Variable	VIF	Comment	
Constant	315.14	High Variance Inflation Factor (VIF) but standard for a constant	
X_2	2.70	Acceptable level	
X_6	3.66	Acceptable level	
X_7	4.73	Elevated but acceptable level	
Conclusion: Multicollinearity is within the normal range (VIF < 10), but a high value for X_7 indicates the possibility of a linear relationship between the features, which is worth considering in further modeling.			
X_2. Environmentally friendly production, million tenge			
2024	53953	Model equation: $X_2 = 130579.21 – 9359.7621 \cdot X_3$	
2025	50448		
2026	46943		
2027	43437		
2028	39932		
2029	36427		
2030	32922		
Quality assessment of the regression model			
Coefficient of determination (R^2)		0.6513	
F-statistics		1.279	
p-value of F-statistics		0.027	
Standard error (S_y)		27509.363	
The № of observations		8	
The № of explicative variables (X_3)		1	
Conclusion: The model with the coefficient of determination $R^2 = 0.6513$ shows that approximately 65% of the changes in the volume of green production are explained by the share of the rural population with incomes below the subsistence level. This evidences the average accuracy of the model.			
Checking for multicollinearity Variance Inflation Factor (VIF)			
Variable	VIF	Comment	
Constant	155.51	High Variance Inflation Factor (VIF), but typical for a constant	
X_3	1.0	No evidence of multicollinearity	
Conclusion: Variable X3 has no multicollinearity. A high VIF for a constant is standard and does not require correction.			

X_9. Environmental protection investments, thousand tenge		
2024	147211708	Model equation: $X_9 = 3480.7528 - 6.01 \cdot X_6 - 0.1617 \cdot X_8$
2025	160123028	
2026	153898435	
2027	153339190	
2028	152779945	
2029	166562409	
2030	168817743	

Quality assessment of the regression model	
Coefficient of determination (R^2)	6.367
F-statistics	1.887
p-value of F-statistics	0.042
Standard error (S_y)	881.583
The № of observations	8
The № of explicative variables (X_8)	2

Conclusion: The model with the coefficient of determination $R^2 = 0.6367$ shows that approximately 64% of the variation in environmental investment is explained by the number of approved EIA projects and environmental publications. This indicates the satisfactory quality of the model. The value of the F-statistics and p-level of significance shows that the model is statistically significant at the 5% level.

Checking for multicollinearity Variance Inflation Factor (VIF)

Variable	VIF	Comment
Constant	132.4	High-variance inflation factor (VIF) that is typical for a constant
X_6	1.18	No evidence of multicollinearity
X_8	1.22	No evidence of multicollinearity

Conclusion: Variables X_6 and X_8 showed no signs of multicollinearity. The high VIF of the constant is a standard phenomenon and does not require intervention.

X_7. Total environmental protection costs, thousand tenge		
2024	506106135	Model equation: $X_7 = 198269862.8259 - 10539721.2219 \cdot X_4 + 1052035.9631\ X_5$
2025	534229934	
2026	562353733	
2027	590477533	
2028	618601332	
2029	646725131	
2030	674848930	

Quality assessment of the regression model	
Coefficient of determination (R^2)	0.8865
F-statistics	15.628
p-value of F-statistics	0.006
Standard error (S_y)	38802293.243
Number of observations	8
Number of explicative variables (X_4, X_5)	2

Conclusion: The model with the coefficient of determination $R^2 = 0.8865$ demonstrates a high degree of explanatory power: almost 89% of the variation in environmental costs can be explained by greenhouse gas emissions from land use and CO_2 emissions. The F-statistics and significance level confirm the statistical significance of the model at a high confidence level (less than 1%).

Checking for multicollinearity Variance Inflation Factor (VIF)

Variable	VIF	Comment
Constant	128.3	High Variance Inflation Factor (VIF) but standard for a constant
X_4	1.21	No evidence of multicollinearity
X_5	1.29	No evidence of multicollinearity

Conclusion: Variables X_4 and X_5 do not show multicollinearity. A high VIF for a constant is a standard phenomenon and does not affect the interpretation of the model.

According to the results presented in Table 4, the predicted values of indicators X_2 and X_9 decrease annually, which may be a consequence of the reduced investment in previous years as a result of the COVID-19 pandemic, socioeconomic crisis in the country, and impact of external economic factors. The forecasting approach described above serves as a foundational tool for performing predictive calculations. In this context, the authors developed a computational algorithm to estimate the regression equations and analyze their statistical properties, which allows for the assessment of the reliability and validity of the resulting parameters [34].

Positive trends were observed for indicators X_1, X_7, and X_9, with a significant increase in the future X_1 and a large increase in X_9. The trend of indicator X_2, namely the number of environmentally friendly products over time, probably decreases if the current inputs are maintained. However, the results of these indicators may change dramatically under the influence of other external factors, such as the adoption of appropriate legislative and other governmental measures, which will either improve the development trends of the indicators of the green economy under study or, conversely, change their course toward deterioration and stagnation.

4-2- Integration of Environmental and Economic Factors

This study emphasizes the importance of combining the environmental and economic aspects for a successful transition to a green economy. Despite efforts to reduce greenhouse gas (GHG) emissions, a significant portion of the industrial production still pollutes the environment. The results of this study emphasize the need for an integrated approach to implementing a green economy in Kazakhstan, with a focus on social, economic, and environmental factors. They also confirm the importance of integrating environmental and economic factors for an effective transition to a green economy. For example, data on greenhouse gas emissions (X_4 and X_5) and environmental costs (X_7) show that despite active efforts to reduce carbon emissions, a significant part of industrial production continues to be a source of pollution. Simultaneously, increased spending on environmental initiatives increases the potential for cleaner production, as evidenced by the increasing share of green production in the economy’s gross output.

As a result, the following analytical assumption can be made: for the sustainable development of a green economy in Kazakhstan, it is necessary to continue the active implementation of environmental standards and stimulate the transition to low-carbon technology. However, this will not be sufficient without increased efforts to reduce emissions in carbon-intensive sectors such as energy and agriculture, which will require stimulating environmentally friendly technologies and strengthening control over the observance of environmental standards.

Considering the relationship between social and environmental policies, poverty reduction and improved social stability support the transition to a green economy. As shown by the share of the rural population with incomes below the subsistence level (X_3), low-income levels can limit opportunities for investment in sustainable development and environmentally friendly technologies, which affects overall environmental performance. Therefore, it is essential to develop comprehensive measures to reduce social inequality in the context of environmental policies. For example, subsidizing environment-friendly technologies in rural areas and supporting local producers can help improve social conditions and stimulate sustainable development at the regional level. We recommend strengthening investments in the education and skill development of the population, which will enhance the awareness and participation of citizens in environmental initiatives.

The role of scientific and educational initiatives in the context of sustainable development is reflected in the growing volume of academic publications in environmental studies (X8). The recent upward trend implies an increasing research focus on issues related to the green economy. This trend supports the view that scientific inquiry and innovation play vital roles in advancing a country’s environmental progress. However, the results of scientific studies should not remain in academic circles but should be applied in practice to solve specific environmental problems. Regarding econometric forecasting and environmental risk management methodology, the forecast values of endogenous variables obtained during the study show that Kazakhstan will continue to face environmental and economic challenges unless a targeted policy to improve the environmental situation is implemented. For example, data on greenhouse gas emissions and environmental costs show that current measures cannot achieve sustainable results without significant effort to reduce carbon emissions and improve energy efficiency.

Based on the analysis of the regional potential of Kazakhstan, including geographical features, a conditional map of promising areas of the green economy by region of Kazakhstan was built, which can help farmers and investors in decision-making on the development of green projects in the country (see Table 6).

Table 6. Conditional map of the green economy development potential in Kazakhstan

Kazakhstan	Green development potential	Green development forms
West regions	1. Outlet to the Caspian Sea 2. Located closer to the European part of the continent 3. International co-operation opportunities 4. Windy climate, warm winters, dry hot summers 5. Many free desert areas	1. Wind, solar and hydroelectric power plants 2. Solar panels 3. Waste recycling 4. Combating desertification and soil degradation
East regions	1. Enough water bodies 2. Wide woodland belt	1. Hydroelectric power plants 2. Organic farming
North regions	1. Severe cold climate 2. Many mining operations 3. Developing cross-border trade	1. Wind, solar and hydroelectric power plants 2. Solar panels 3. Organic farming
South regions	1. Warm climate 2. Developed agriculture 3. Prerequisites for developing organic agricultural production on a large scale 4. Developed and busy trade and logistics infrastructure	1. Wind, solar and hydroelectric power plants 2. Solar panels 3. Organic farming 4. Water-saving technologies
Central regions	1. Many mining enterprises 2. Developed transportation and urban infrastructure 3. Plenty of agricultural land	1. Wind and solar power plants 2. Organic farming 3. Solar panels 4. Closed-loop animal husbandry 5. Waste recycling 6. Forest replantation 7. Urban green farms

Thus, the data in Table 6 contains a precise division of possible green areas, including renewable energy and organic farming, in the five major geographical areas. In addition, it indicates the advantages and disadvantages of each region in various aspects of interest for green decision making. For example, the western part of the country, including Mangystau, Atyrau, Aktobe, and West Kazakhstan, has many geographical advantages for developing international renewable energy projects. However, this region is characterized by a severe climate, predominantly desert land, and a shortage of fresh water for agricultural purposes.

Climate change and unpredictable natural disasters have led to the need for efficient land use by irrigating oases through reconstruction and construction. The main task facing the AIC of Kazakhstan is to build, based on the inefficient and outdated AIC, a competitive and unique sector of the economy that would provide mainstream support to the entire economic system without causing even more damage to the country's environment.

4-3- Effective Management of the Transition to a Green Economy

Consequently, many questions arise related to the administration and management of agro-industrial complex AIC processes, namely their change in environmental friendliness, efficiency, and safety for the end users of agricultural products. To answer these questions and to better understand the possibilities of the AIC transition to a green economy, a scheme (model) of process management with the indication of stakeholders involved in achieving results was developed (Figure 2).

The successful transition of the agro-industrial complex (AIC) of Kazakhstan to a green economy requires the active participation of various stakeholders who play an important role in this process (Figure 2).

Government agencies are responsible for the formation and implementation of sustainable development policies, development of regulatory frameworks, and creation of mechanisms to support businesses and farmers. They regulate the implementation of environmental standards, provide subsidies for developing green technologies, and ensure compliance with the environmental regulations. In addition, the state plays a leading role in attracting investment and creating conditions for Kazakhstan's integration into international sustainable development initiatives.

Equally important is the contribution of businesses and agribusinesses, which should introduce energy- and water-saving technologies, minimize the carbon footprint, and promote environmentally friendly production. Public-private partnerships play an essential role in financing and implementing environmental initiatives. However, sustainable transition is impossible without the active participation of farmers and agricultural cooperatives. As direct implementers, farmers should introduce organic farming, optimize resource use, and improve management efficiency. They must receive state support and access to educational programs that allow them to master new technologies.

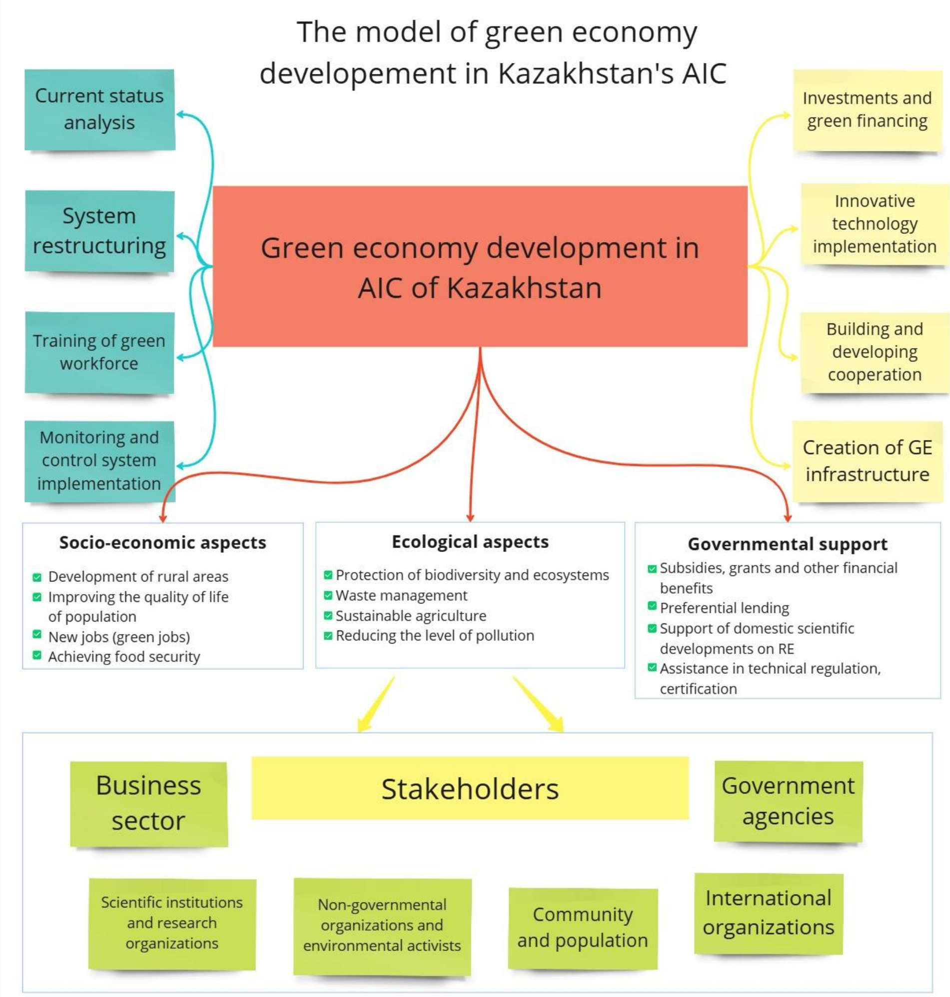

Figure 2. Model of AIC green economy development in Kazakhstan

Scientific and educational institutions, in turn, ensure the development of scientific studies in green agriculture and transfer of knowledge to the real sector. Therefore, science should develop new methods and technologies to promote practical applications. Investigations into digitalization, sustainable farming, and organic production, which can significantly improve AIC efficiency, are essential. However, this requires a close connection between research centers, businesses, and the government to ensure the rapid introduction of development into production.

Environmental non-government organizations (NGOs) also play an essential role in this process. They acted as independent supervisors in compliance with environmental standards, conducted educational campaigns, and promoted environmental awareness among the population. Their work aims to protect the environment, promote environment-friendly products, and cooperate with government agencies to develop and implement green economic initiatives.

International organizations and investors complement this process by providing Kazakhstan with financial, technological, and expert support. International co-operation opens opportunities for introducing advanced solutions in sustainable agriculture, attracting foreign investment and entering world markets for domestic producers. Kazakhstan has already participated in a range of international programs for developing a green economy; however, a full-scale transition requires broader co-operation and the application of world experience.

Thus, the synergy of stakeholders allows Kazakhstan to create a sustainable, competitive, and environment-friendly agro-industrial system. The state should create conditions to support green initiatives, businesses to introduce innovations, farmers to apply sustainable production methods, science to develop new technologies, and public organizations and international partners to promote development and monitor compliance with environmental standards. The synergy between these efforts ensures a successful transition to a green economy and increases the competitiveness of Kazakhstan's agriculture in the international arena. To achieve visible results in adapting the existing AIC model to a green economy, it is necessary to consider the management of all processes that constitute the existing model and the roles of all stakeholders. For this purpose, the model presented in this study can clarify the directions that should be used in implementing green economy tools such as green technologies, investment, government support, and staff training.

Investments in green agriculture have long-term strategic importance for preserving agricultural land and ensuring food security in Kazakhstan. Market participants should implement closed-cycle models, develop precision agriculture, avoid uncontrolled use of mineral fertilizers and pesticides, reclaim land more actively, and observe crop rotation. Unfortunately, producers have little incentive to allocate additional funds; therefore, the role of the state in such issues is of paramount importance. The authors considered the creation of an effective system of public environmental control as a tool for developing a green economy.

5- Discussion

We define the main provisions based on the authors' multilateral analysis. Despite the long existence and disclosure of the principles of the green economy in the world environment of economic science, domestic scientists have paid little attention to this direction, and existing studies are fragmentary. They cannot provide a complete picture of the use and implementation of their results in the real economy of a country.

Green economic development refers to the transition to more sustainable and environmentally friendly methods of production and consumption to balance the economic, social, and environmental aspects of development. Within the framework of green economy development in Kazakhstan, the following trends in the agricultural sector development are observed:

- Shifting toward organic agriculture and other environmentally compatible farming practices can contribute to decreasing the use of chemical fertilizers and pesticides, enhancing soil health [35], and mitigating harmful effects on the environment.
- The implementation of advanced technologies and improved management strategies aimed at optimizing the use of water, energy, and other resources is essential to minimize excessive consumption and limit environmental degradation.
- The use of digital solutions and innovative technologies will improve the efficiency of agricultural production [36], including soil and plant monitoring, irrigation optimization, and data management for decision-making.
- This includes providing social assistance through locally produced agricultural products from green enterprises for socially vulnerable groups, especially children, pregnant women, and people with disabilities, with clean and healthy agricultural products.
- Its introduction to agriculture will help reduce the negative environmental impacts of composting and recycling of organic waste.
- The expansion of employment opportunities in environmentally oriented sectors, along with the retraining of the existing workforce to align with the ecological and resource-efficient practices in the agribusiness sector, represents a crucial component of sustainable development.
- The advancement of green financing mechanisms is expected to stimulate the inflow of international investment into environmentally sustainable projects, including those in agriculture, by establishing favorable and priority conditions for investors.

The level of investment in environmental protection and the growing attention from scientific research and development, reflected in the indicators of the factor of the number of publications in the environmental sphere, significantly affect the environmentally friendly production and final gross output of agricultural, forestry, and fishery products (services) in Kazakhstan. At the same time, to boost foreign investment in the green development of the country's agricultural sector, it is essential to build a green finance market in the region. This relatively new type of financial sector is still in its early stages of development in Kazakhstan and is a promising area and one of the pillars of green economic development. The main challenges to the development of green financing in the country are the high risks associated with green projects, long payback periods, immature production infrastructure, and insufficient regulatory and legal support for this type of financing [37].

The results of this study emphasize the complex and multifaceted nature of the transition to a green economy in Kazakhstan, which in turn requires the integration of environmental and economic aspects. In addition, comparing the results with data from other relevant studies on similar topics provides an opportunity to interpret the results in more detail. For example, Wang et al. [38] emphasizes the relationship between environmental standards and agro-industrial performance. This opinion is consistent with our findings that increased spending on environmental initiatives will stimulate green production while highlighting the need for stricter compliance with environmental standards to prevent pollution from worsening. It is also interesting to note the results of Gupta et al. [39], who pointed to the importance of investment in new technologies, as well as research and development (R&D) for sustainable agriculture in the face of climate change. However, our projections show that, without fundamental changes in policies and practices for adopting such technologies, genuine positive changes in green economic performance may be unachievable. This approach runs counter to the optimistic assessment of future sustainable change presented in previous studies, implying the need to revise existing forecasting models.

The projected values generated by this model, derived from the dynamics of various economic processes, demonstrate a sufficient level of reliability for application in decision-making contexts [40]. Consequently, the use of this approach is justified in developing a dynamic multifactor forecasting framework. The innovative development of AIC in the context of implementing green economy projects can be analyzed using various models. However, it is necessary to correctly identify the main factors that directly affect the effectiveness of AIC modernization in a green economy [41]. Similar studies have been conducted on the indicators of sustainability and green economy. Researchers emphasize the following features of sustainable development indicators: accessibility in time dynamics, informativeness, equivalence, and the limited number of indicators included in the indicator system [42]. However, it is worth noting that in Kazakhstan, scientists face the problem of availability of reliable research and statistical data, especially regarding data related to the green economy.

A comparison of existing research reveals that current methodological approaches often overlook the influence of key socioeconomic variables, including poverty rate and access to education. Koch et al. [34] similarly emphasized that social dimensions constitute a critical component of a comprehensive approach to the green economy. Our work confirms the need to develop policy measures to reduce social inequalities because favorable social conditions can equip the population with resources to adopt sustainable technologies and practices [43]. Therefore, the synergy between economic, social, and environmental factors can be the key to successful progress toward the transformation of Kazakhstan’s economy.

The proposed model for developing Kazakhstan’s agro-industrial complex differs fundamentally from earlier models by focusing on the critical need to revise the existing strategic documents. This revision involves a more balanced distribution of investments and reinforcement of sustainable development principles across all stages of production and related processes within the agro-industrial sector. A distinctive feature of this model is its comprehensive approach, which considers the regional characteristics of Kazakhstan’s diverse territories during its transition to a green economy. In our assessment, the current strategic documents in force in Kazakhstan, such as the “Green Economy Concept” and the “Kazakhstan 2050 Strategy,” do not fully incorporate the indicators that form the basis of our model. Additionally, they lack concrete guidance and effective tools to ensure successful transition to a green economy within the agricultural sector.

Alongside the econometric and forecasting analysis of the main drivers influencing green economy development, this study offers a set of practical recommendations and specific measures for the implementation of green principles in Kazakhstan’s agro-industrial sector. Thus, the results of our study indicate the need for a more comprehensive approach to integrate the various factors affecting a green economy. Considering the findings of other authors, we can say that to achieve the desired results in sustainable development, we must introduce modern technologies and change the mindset at the state level and among end consumers. This idea requires scientific and practical investigation and active participation of all stakeholders in forming new approaches and policies for a sustainable economy at all levels.

6- Conclusion

6-1- General Conclusions

Despite global community awareness about the importance of the green agenda for more than three decades, EAEU countries, especially Kazakhstan, only want to advance explicit actions to introduce a green economy into the agro-industrial complex (AIC). This study emphasizes the importance of an integrated approach to the development and implementation of green technologies in the AIC of Kazakhstan. Only the joint efforts of the state, business, scientific institutions, and public organizations can lead to a successful transition to a sustainable and environmentally friendly economy.

Following the forecast model, the value of the necessary investments in environmental protection was determined, demonstrating the need to increase these expenditures. For example, in 2023, according to local statistics in Kazakhstan, the share of investment in environmental protection was only 0,98% of the total investment in capital assets and 15% of the total investment in GDP. Unfortunately, despite a possible increase in environmental support by 2030, the indicator of green production showed an overall downward trend. The results can be used to develop recommendations for planning environmental protection costs and determining investment indicators for sustainable development in Kazakhstan. Therefore, it is necessary to strengthen the knowledge transfer mechanisms between scientific institutions and industrial enterprises, as well as between government agencies and educational institutions. Implementing this recommendation will accelerate the introduction of environmental innovations and technologies at the industrial level, and increase the effectiveness of environmental policies.

To minimize environmental risks and prevent economic losses associated with environmental problems, it is necessary to develop more rigorous forecasting models to assess the impact of environmental and economic factors on long-term development. Forecasting should include an analysis of current trends and possible scenarios based on global environmental and economic changes for more accurate planning of measures to adapt to and overcome possible risks.

Based on data analysis, the following recommendations for public policy and practice can be formulated:

- Strengthening tax incentives for green technologies – in other words, introducing additional tax incentives and subsidies for businesses switching to low-carbon technologies – will accelerate the green transformation process. This approach will help reduce carbon emissions and stimulate growth in innovative sectors of the economy.
- Stimulating social inclusiveness in environmental initiatives; in other words, directing efforts to reduce social inequality in green transformation. It is essential to prioritize the support of rural communities and socially vulnerable groups through the creation of additional employment opportunities and implementation of targeted training initiatives, thereby fostering inclusive participation in the transition toward sustainable development.
- Investment in infrastructure for green growth, that is, developing infrastructure for a green economy, including waste treatment systems and solar and wind power plants, can be an essential step in increasing the share of clean energy in the country's total energy balance. This will significantly reduce dependence on fossil energy sources and greenhouse gas emissions.

The results obtained can provide a theoretical and practical basis for improving knowledge regarding the green economy and its application in the agricultural sector.

6-2- Theoretical Contributions

The results of this study contribute significantly to theoretical science, particularly in econometrics and ecology. Applying a multifactor regression model to analyze and forecast indicators of the green economy in Kazakhstan makes it possible to identify the key factors affecting economic performance and assess their interrelationships. This approach provides a basis for further investigations to optimize economic processes while considering environmental aspects. Statistical methods, such as the multiple correlation coefficient and Fisher's criterion, ensure the reliability of the results and allow reasonable conclusions regarding the significance of factors, which is essential for the theoretical justification of economic models.

In addition, this study highlights the need to integrate environmental and economic factors into the successful transition to a sustainable economy. This integration opens new horizons for theoretical development concerning the interaction between economic growth and environmental sustainability. In particular, the emphasis on the importance of social factors such as income levels and access to environmentally friendly technologies highlights the need for an integrated approach to address inequality and environmental policy in Kazakhstan. This can form the basis for future studies aimed at developing efficient sustainable development strategies and policies.

6-3- Practical Implications

The results of this study contribute to the development of the green economy in Kazakhstan's AIC and the scientific community by providing specific data and forecasts to shape public policy and sustainable development strategies. Forecasting models based on multifactor analysis allow government bodies and local administrations to make informed decisions regarding investments in environment-friendly technologies and initiatives. This can help in the development of programs to reduce greenhouse gas emissions and improve a country's environmental conditions.

In addition, the results of this study can be helpful to businesses, especially in sectors related to agriculture, energy, and environmental technologies. Companies can use these findings to assess the risks and opportunities for adopting sustainable practices. For example, understanding the impact of various factors on productivity and environmental costs can help businesses optimize their processes, reduce costs, and increase competitiveness in the market. It can also help attract investment in green projects, which are an essential component of economic growth.

Finally, the results of this study can be used by educational and scientific institutions to develop curricula and courses aimed at training ecological and sustainable development professionals. An increase in the number of publications and scientific studies in this area can raise awareness of the importance of environmental initiatives and stimulate active participation of students and researchers in solving current environmental problems. Thus, the results of this study have a broad range of applications, and can contribute to the economic and social development of the country.

6-4- Research Limitations

The main limitations of our study include the lack of completeness of the strategic documents on which this study relies, such as the "Concept of Transition to a Green Economy." In particular, the concept lacks a clear plan for the agricultural sector, hindering the understanding and implementation of specific activities and mechanisms within the AIC. The conclusions drawn from this research should be viewed as advisory and general in nature given the broad scope of the subject matter. This breadth may impose certain limitations on the practical application of these findings. In addition, the authors faced problems with access to reliable statistical data, which hindered the analysis and forecasting of the transition to a green economy in the Republic of Kazakhstan. Econometric models require the correct definition of the factors affecting the efficiency of AIC modernization. Incompleteness or incorrectness of the selected variables can distort the model results.

The selected model does not consider the influence of external shocks and changes in the global economic environment, such as fluctuations in energy prices or political changes in the world economy, which can significantly affect the forecasts.

Another essential limitation is that these studies on the green economy in Kazakhstan often focus on academic institutions and are not applied in practice, which narrows their influence on actual changes in the agribusiness sector. Even if there are recommendations for the transition to a green economy, their implementation may face administrative, financial, and cultural barriers, which limit the practical application of the results of this study.

6-5- Future Research Directions

Kazakhstan exhibits substantial regional variation, including climatic and geographical conditions, differences in population distribution, socioeconomic disparities, and diversity in the dominant types of agricultural production. Analyzing these regional characteristics provides a foundation for assessing the readiness of different areas to transition to a green economy and for formulating appropriate strategies for this transition. Moreover, elements of green principles and practices are already partially implemented by agricultural enterprises in several regions.

Some of the key climatic and geographical distinctions that are largely influenced by the country's vast land area and lack of direct access to the sea are presented in Table 6. Further exploration of these regional disparities should be pursued in future research in this domain.

Further research is required to conduct a more in-depth examination of the role of social and economic factors in shaping the green economy, as well as to develop advanced models that account for regional specificities within Kazakhstan. In addition, future studies should explore the potential influence of international best practices and technological innovations on the advancement of Kazakhstan's green economy, thereby contributing to the formulation of more effective strategies and policy measures. Another key area is the consideration of external shocks and changes in the global economic environment. For example, fluctuations in energy prices, changes in climatic conditions, and international initiatives to reduce greenhouse gas emissions can significantly affect the effectiveness of the proposed model. Therefore, in the future, scenario analysis will need to consider the various macroeconomic and environmental factors that affect the projected indicators.

With adequate development of the green economy in the AIC of Kazakhstan, there is vast space for further study and implementation of green technologies suitable for Kazakhstan, considering the specifics of development and location for the creation of development models integrated with specific business ideas for small farms and agricultural cooperative associations, as well as government agencies.

7- Declarations

7-1- Author Contributions

Conceptualization, D.S. and S.S.; methodology, K.B.; software, C.T.; validation, D.S., S.S., and G.B.; formal analysis, A.K.; investigation, D.S.; resources, S.S.; data curation, K.B.; writing—original draft preparation, D.S., S.S., K.B., G.B., A.K., and C.T.; writing—review and editing, D.S., S.S., K.B., G.B., A.K., and C.T.; visualization, C.T.; supervision, G.B.; project administration, S.S. All authors have read and agreed to the published version of the manuscript.

7-2- Data Availability Statement

The data presented in this study are available in the article.

7-3- Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7-4- Institutional Review Board Statement

Not applicable.

7-5- Informed Consent Statement

Not applicable.

7-6- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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