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Mathematical Modeling of Innovative Processes for Sustainable Development in the Agro-Industrial Complex

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ABSTRACT: Various predictive calculations are actively used in modern scientific research, and economic and mathematical models are becoming particularly important. These methods and approaches are especially appreciated in the production environment, where they contribute to process optimization and informed decision-making. However, in the context of the development of industrial and economic activity, more and more enterprises are faced with the need to introduce mathematical models to improve the efficiency of innovation process management, which allows them to adapt to rapidly changing conditions and industry requirements. In this study, innovation processes are considered through the prism of the principles of sustainable development, which allows us to form the basis for interrelated concepts such as sustainable economy, cluster economy and industrial ecology. The practical significance of this research lies in its ability to offer a theoretical basis, empirical findings, and actionable recommendations for integrating sustainable development policies. These insights facilitate the transformation of innovation processes into a sustainable economic framework. The findings serve as a foundation for formulating strategies, policies, programs, roadmaps, and business models at multiple levels—macro, meso, and micro—within the agro-industrial sector.

Keywords: agro-industrial complex, sustainable development, Sdgs, innovation, innovation process, stages of innovation, economy, human capital, innovative development.

I. INTRODUCTION

Currently, the agro-industrial complex occupies an important place in the priorities of socio-economic policy. On the one hand, the positive results achieved in recent years create the basis for further development of the industry. On the other hand, the development of agriculture, especially agriculture, faces economic and financial difficulties. In the current conditions, it is impossible to ensure the sustainable development of the agro-industrial complex without the introduction of innovations. Innovative activity becomes a necessary condition for the modernization of the agro-industrial complex, the renewal of its material and technical base, the development of markets for agricultural products and the development of advanced technologies. In order to increase the competitiveness and sustainable development of the agro-industrial complex in the future, an active build-up of scientific potential and the introduction of innovative solutions is required. It is generally believed that the Austrian economist Joseph Schumpeter (1883-1950) was the first to introduce the term "innovation". He considered innovation as a process of commercialization of new combinations, providing changes in the development of organizations and the economy as a whole. In his theory, Schumpeter identified five key types of innovation: 1) the creation of new products; 2) the development of new markets; 3) the introduction of new technologies; 4) the discovery of new sources of raw materials; 5) the organization of new types of production [1]. Over time, the term "innovation" has undergone significant changes in interpretation and continues to be a concept that does not have a single definition. The concept of "innovation" has expanded beyond the sphere of production and now also covers organizational, financial and other areas that contribute to the effectiveness of a particular object - an industry, an enterprise. This broad scope actualizes the question of the need to specify and clarify the conceptual framework in this area. Let's consider several modern approaches to the definition of the term, reflecting its multifaceted nature. Innovation should be considered only those innovations that bring benefits (positive economic, social, environmental or other effects, as well as their combination) [2]. R.A. Fatkhutdinov, analyzing the essence of innovation, offers an integrative approach that combines the process and product aspects. He argues that "innovation is the final result of the introduction of innovations aimed at transforming the object of management and achieving economic, social, environmental, scientific, technical or other effects" [3]. This approach focuses not only on novelty as such, but also on the effectiveness of implementation, as well as on the variety of positive effects that innovations can provide for various aspects of activity. I. V. Afonin focuses on the fact that innovation is a "purposeful and intensive process aimed at obtaining a new applied result with a potential, rather close in time socio-economic usefulness with a high probability" [4]. This definition emphasizes the dynamism of the innovation process and its focus on practical application, which makes it an important tool for achieving significant economic and social results. The main approaches to the definition of the term "innovation" in foreign studies have identified the presence of basic interpretations: as a process [5, 6, 7, 8] as a change [9, 10, 11]; as a result [12, 13, 14].

The primary research objectives include: (1) Identifying the critical factors influencing innovation efficiency in the agro-industrial complex; (2) Developing a predictive model to assess the impact of various policies on innovation dynamics; (3) Providing actionable insights to align industrial innovation with sustainable development principles. This study examines innovation processes through the lens of sustainable development principles, establishing a foundation for interconnected concepts such as a sustainable economy, cluster economy, and industrial ecology. The research employs statistical data from the 2030 Sustainable Development Goals (SDG) monitoring platform, the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, and the Food and Agriculture Organization of the United Nations. The proposed approach was tested within the agro-industrial complex, utilizing a forecast model to predict the development of an innovative economy in Kazakhstan from 2022 to 2030. The mathematical modeling framework employed in this research allows for scenario analysis, predictive assessments, and the evaluation of various policy impacts on innovation dynamics. By integrating quantitative methods, the study provides a structured approach to solving inefficiencies in innovation management while ensuring alignment with sustainability objectives. An approach in which innovation is considered as a result seems logical, given that innovation has a significant process component. In the context of the agro-industrial complex, the conceptual aspects of innovation should be changes in the following areas: organization of agricultural enterprises, development and improvement of products and services, creation and introduction of new technologies. These changes should lead to the creation of conditions that ensure food security, as well as an increase in the level and quality of environmental and social well-being of rural areas. Ultimately, such changes also contribute to increasing the competitiveness of the agricultural sector.

II. MATERIALS AND METHODS

The "Concept for the development of the agro–industrial complex of the Republic of Kazakhstan for 2021-2030" highlights the key trends determining the creation and implementation of innovations in this area (On approval of the Concept for the Development of the agro–industrial complex of the Republic of Kazakhstan for 2021-2030, Resolution of the Government of the Republic of Kazakhstan dated December 30, 2021 No. 960). These trends emphasize the need for a comprehensive approach to the modernization of the agro-industrial complex. This includes not only the intensification of private investment, but also the deepening of the relationship between scientific research and practical needs, as well as the development of internal capacity to create competitive technologies. In the field of economic research, the factors influencing the innovative development of agriculture are usually divided into internal and external. These factors, according to the author, include (Figure1):

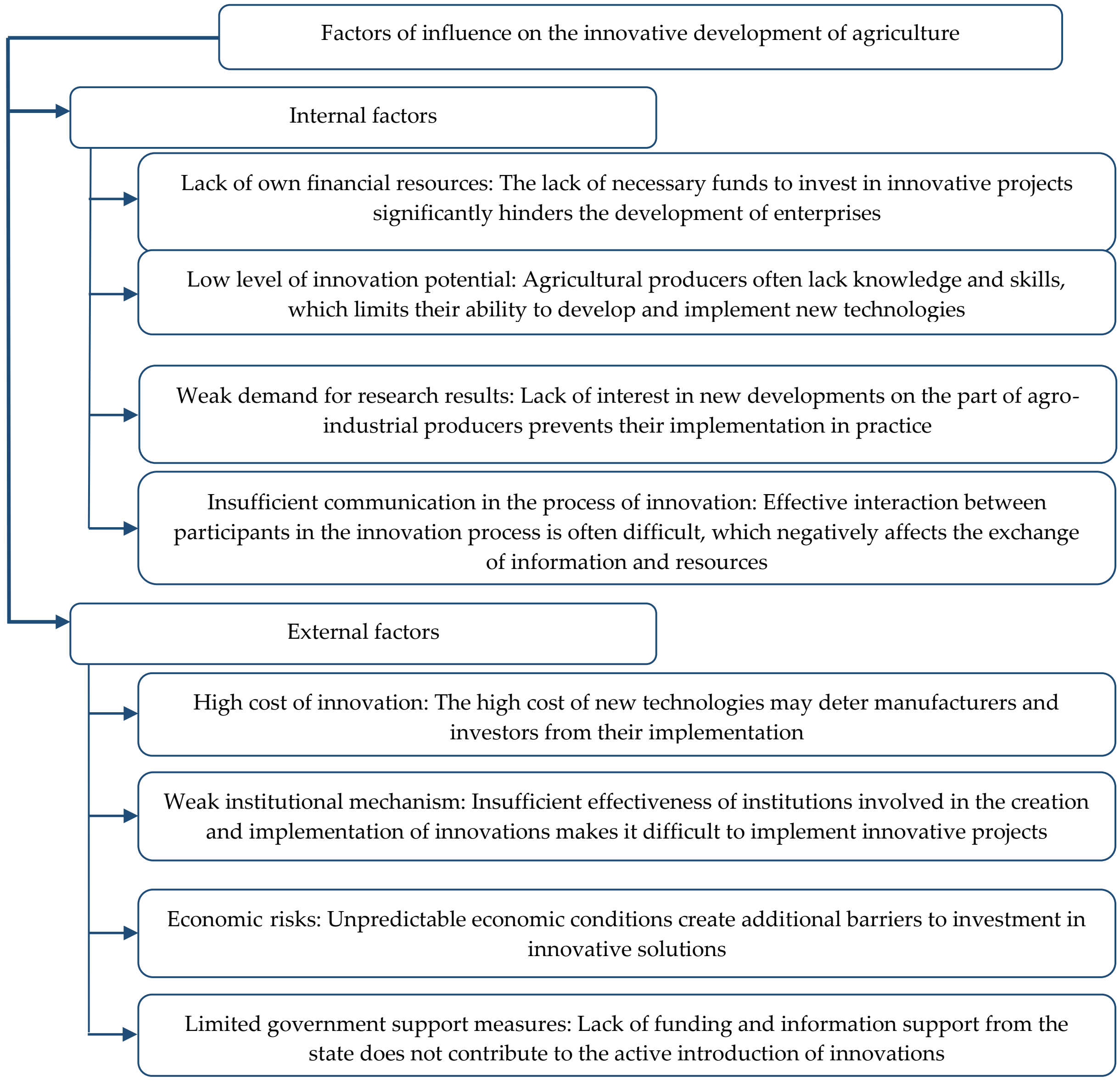

FIGURE 1. Factors influencing the innovative development of agriculture.

The elimination of these internal and external barriers is critically important for the effective development of the innovative potential of the agro-industrial complex. This, in turn, will lead to its steady progress and increased competitiveness in the modern market.

The most significant factors hindering innovative development remain:

1. Lack of own funds in organizations (20.5%): This is the dominant obstacle, as it limits opportunities for investment in new technologies and modernization.
2. High cost of innovation (15.3%): This factor ranks second in importance, since the high price of new solutions can become a barrier to their implementation and adaptation in production processes.

These two aspects highlight the need to develop comprehensive strategies to support organizations in obtaining the necessary resources and reducing the cost of innovation. The implementation of such measures will help to create a more favorable environment for innovation and make the agro-industrial complex more adaptive to the challenges of our time (Figure 2).

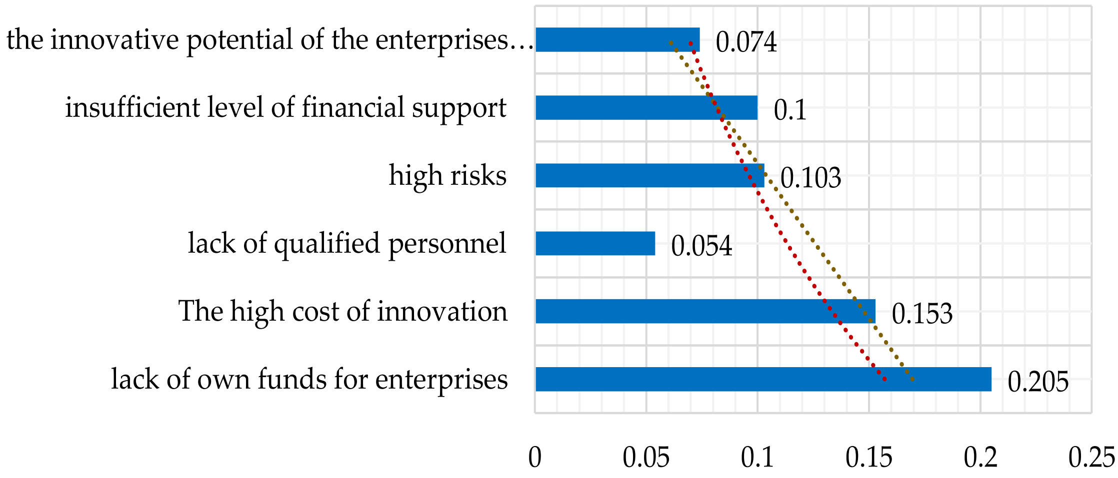

FIGURE 2. Factors constraining the development of the innovative component of the industry https://stat.gov.kz/ru/.

These factors objectively affect the innovative potential of the enterprises themselves, reducing its effectiveness. In particular, the lack of financial resources and the high cost of innovation have a significant impact on the level of innovation potential (7.4%). In turn, high risks (10.3%) and insufficient financial support (10.0%) also become serious obstacles to development. This statement, in our opinion, is controversial, since a low level of support can be both a consequence and a cause of other problems in innovation. To address issues related to the shortage of qualified personnel (5.4%), comprehensive measures can be implemented to support universities and educational institutions in training specialists necessary for the agro-industrial complex [15]. These listed factors create significant barriers to the introduction and expansion of innovations, which emphasizes the need to identify targets to overcome them. One of such targets is the principle of the National Development Plan of the Republic of Kazakhstan "Building a diversified and innovative economy". This principle implies an increase in innovative activity in agriculture by 30% (Figure 3), as well as attracting investments, which will become the basis for future growth and sustainable development of the agro-industrial complex (Figure 4).

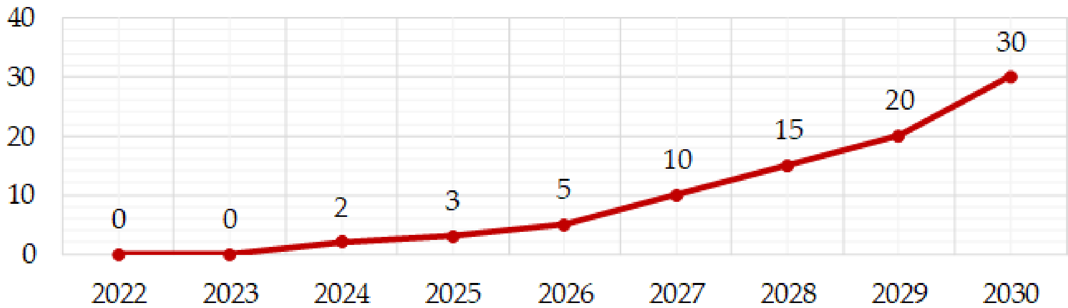

FIGURE 3. Increasing innovation activity in agriculture for 2022-2030, %https://legalacts.egov.kz/npa/view?id=14924428.

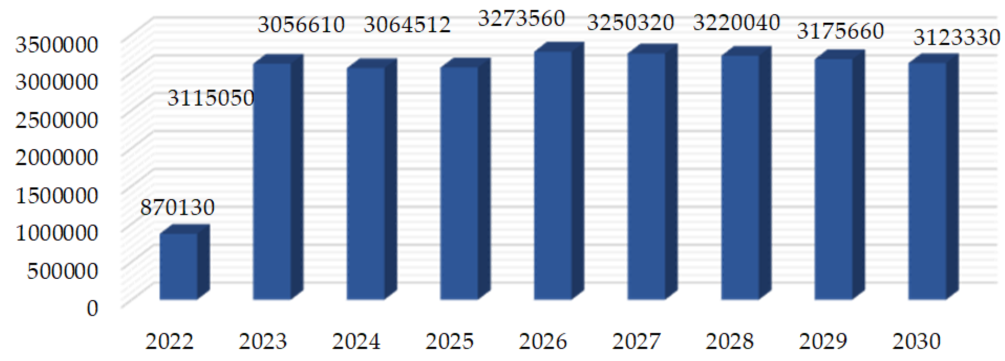

FIGURE 4. Attracting investments in agriculture 2022-2030, thousand tenge, https://adilet.zan.kz/rus/docs/P2100000960.

III. RESULTS

According to the results of the expert survey, the key motivations for increasing innovation in the agro-industrial complex are not so much the creation of new or unique products, as the desire to reduce and minimize the risks associated with agricultural production. Experts note that in conditions of uncertainty and fluctuations in market prices, it is risk management that becomes the primary task. This includes both the optimization of production processes and the introduction of modern technologies that enhance resilience to external factors. Thus, innovative solutions should primarily focus on improving the reliability and predictability of agricultural results, which is the main priority for market participants (Figure 5).

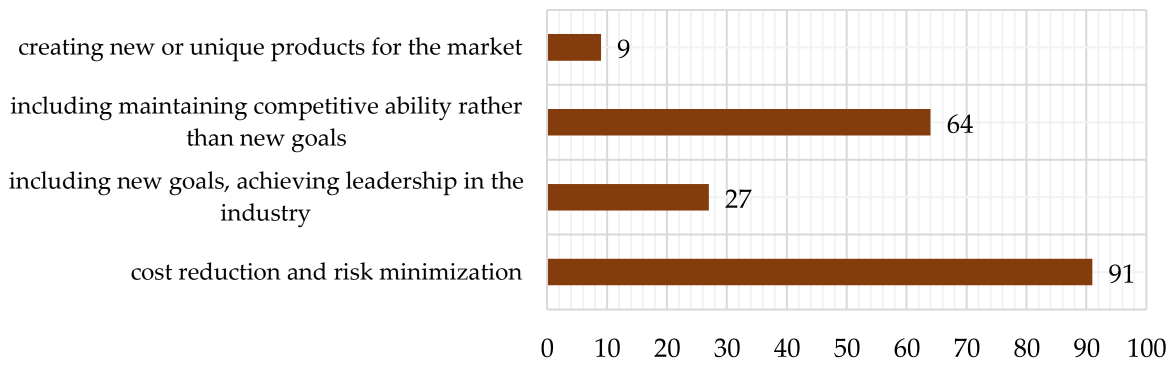

FIGURE 5. Key motives for the growth of agricultural innovation, % https://faolex.fao.org/docs/pdf/kaz212343.pdf.

The key motives for the growth of innovation in the agro-industrial complex have predetermined priority areas for innovation investment (Figure 6).

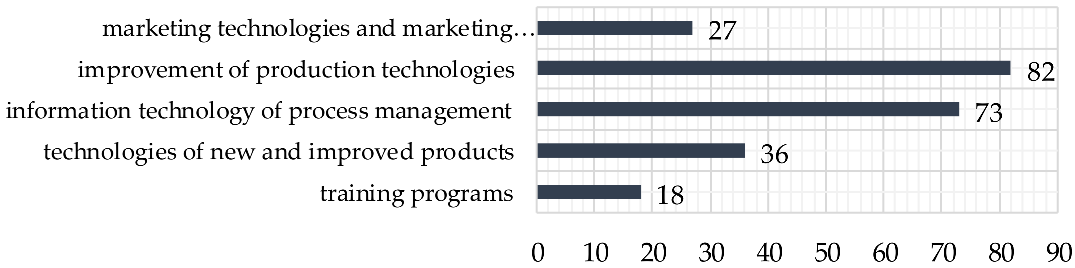

FIGURE 6. Rating of priority areas of investment in innovation, % https://faolex.fao.org/docs/pdf/kaz212343.pdf

Experts have identified promising areas that will radically transform agricultural production in the next 10-20 years: the cultivation of varieties of crops (drought-resistant), the need for which will determine global climate change; increased crop yields; the appearance of meat products of non-animal origin; it is assumed that by 2040 only 40% of meat products consumed by the Earth's population will be of animal origin; the use of agrodrons (according to statistics, every 10 enterprises have already introduced this technology into their activities; thus, during the pandemic period, one can observe an increase in the level of interest of representatives of the agricultural industry in innovative technologies.

The key directions of innovative development of the agro-industrial complex can be represented by the following blocks (Figure 7).

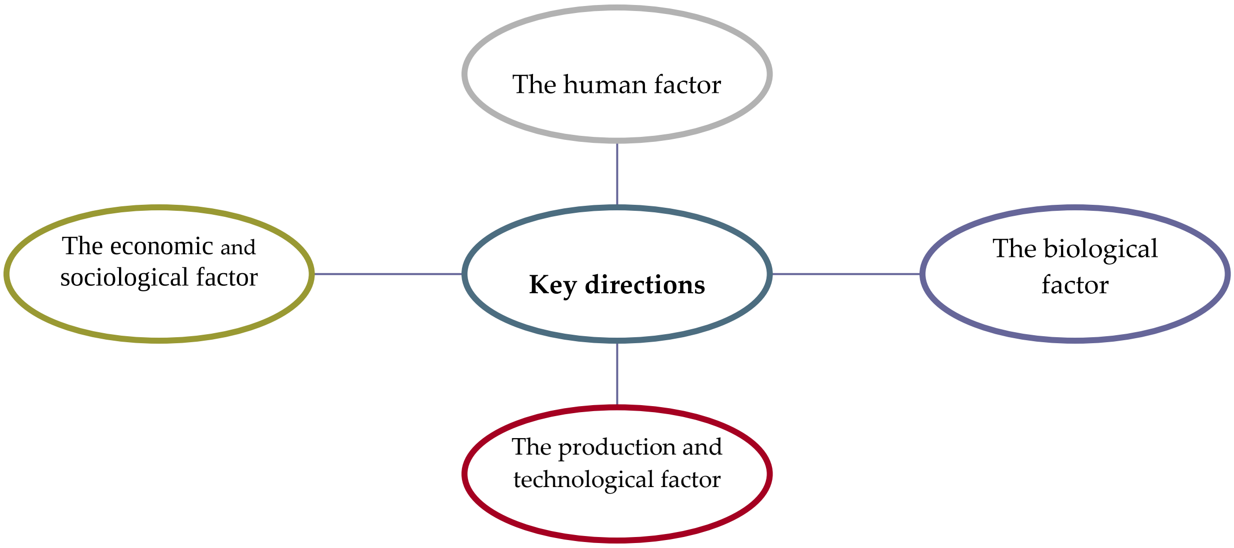

FIGURE 7. Key directions of innovative development of the agro-industrial complex

To promote scientific and technological achievements and effectively solve existing problems, it is important to create information and consulting services. Their main task will be to enhance innovation processes and technology transfer. It is important that the responsibility for the adaptation of research and development lies with the regional offices of such services, which will take into account the natural and economic conditions of each region.

Creating "packaged" products to promote domestic innovations is becoming an important task in this context. This includes the development of additional documents related to crop cultivation technologies, animal husbandry, such as feed, design of production facilities, assortment of recommended agrochemicals, as well as consulting services and other aspects. The possibility of integrating such packages into the agricultural leasing system is also not excluded. Educational institutions, scientific organizations and management bodies of the agro-industrial complex should take responsibility for the formation of Kazakhstan's package innovative solutions. In addition, A. Golubev proposes to provide state support for scientific research based on actual research results, and subsidies should be directed to producers of scientific products in demand in agriculture [16].

The results of the expert survey showed that the following innovations will have the greatest impact on the development of the agro-industrial complex (Figure 8).

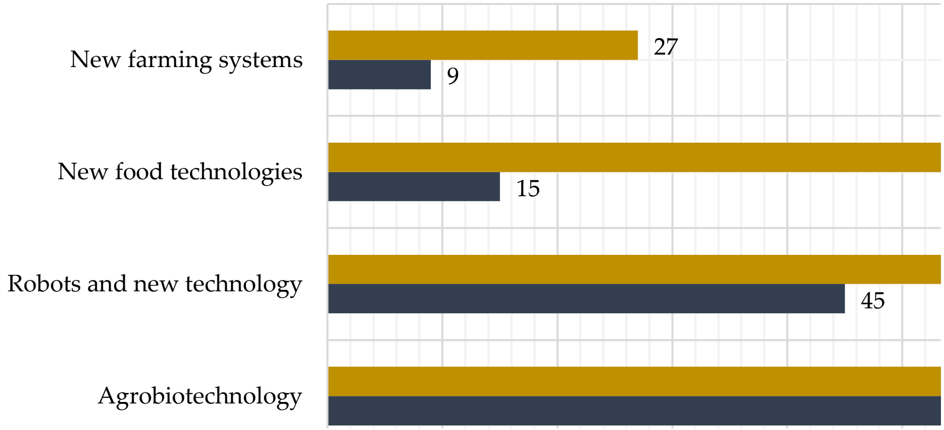

FIGURE 8. Rating of the impact of key technologies and trends https://stat.gov.kz/.

Information technology is in the first place in the ranking. According to experts, digitalization and the introduction of the Internet of Things will be the main factors influencing the innovative development of the industry in the coming years. Digitalization of agriculture includes two key components: digitalization of public administration processes (state support) in the agricultural sector and digitalization of agricultural production itself.

The introduction of digital technologies will affect the process of agricultural production, contributing to an increase in production volumes focused on import substitution and export demand. This, in turn, will ensure food security and independence in modern Kazakhstan, as well as increase its competitiveness [17].

The following can be considered relevant directions for the development of innovations in the agro-industrial complex: the introduction and development of information technologies, the creation of new technologies for food production and farming systems, the use of agricultural robots and automated equipment, as well as the improvement of agrobiotechnologies [18].

The slow pace of the introduction of innovative technologies in the agro-industrial complex and the often-complete lack of financial resources for most agricultural producers require increased attention from the state. It is logical that a deeper study of the issues and significant financial support from the government are needed, as well as an understanding of the importance of implementing innovative projects. The main task of the state is to create conditions for the formation of a favorable investment climate [19].

The results of the survey on what measures of state support for innovation business expects showed the following data: in the first place in importance are measures to optimize the regulatory environment, which 91% of respondents expect. 82% of respondents expect financial support, 64% are interested in strengthening scientific and human resources, and 9% need help to overcome market barriers.

The opportunities for innovative development of the agro-industrial complex are as follows: strengthening scientific and human potential, developing rural infrastructure to improve the environmental and social well-being of the population, increasing financial literacy of agricultural producers in the context of the introduction and use of information technologies, expanding grant support, which is especially important for the introduction of innovations in the field of biological and industrial-technological factors, attracting private companies willing to invest in R&D, through the provision of subsidies and active tax incentives, the use of the potential for the implementation of PPP projects, the development of new and improvement of existing mechanisms for subsidizing scientific research, the provision of preferences to commercial organizations engaged in scientific research at their own expense [20].

This study used mathematical modelling methods, statistical data obtained from official sources: the Committee on Statistics of the Republic of Kazakhstan, official reports of the Ministry of Trade and Integration of the Republic of Kazakhstan, the Ministry of National Economy of the Republic of Kazakhstan, the Ministry of Finance of the Republic of Kazakhstan, the Ministry of Industry and Infrastructure Development of the Republic of Kazakhstan, the Ministry of Digital Development, Innovation and Aerospace Industry of the Republic of Kazakhstan. Mathematical models of economic development.

Despite these changes and the fact that the Asian region is rapidly catching up with North America and Europe, other regions of the world, especially Latin America and the Caribbean and sub-Saharan Africa, are lagging behind and require urgent attention.

The short- and long-term impacts of the COVID-19 pandemic, current geopolitical instability, monetary tightening, and the effects of shocks to global supply chains and global innovation networks on nascent innovation systems in middle- and low-income countries require close monitoring.

Table 1. Quantitative results of experiments.

X1								
1000	936	864	324	360	396	288	288	144
988	926	874	314	362	388	276	290	150
992	930	868	321	358	392	284	284	148
990	932	870	318	356	390	280	286	152
995	932	870	318	356	392	284	284	148
1001	930	868	321	358	390	280	286	152
994	926	874	314	362	388	276	290	150
990	930	868	314	362	392	284	284	148
985	930	868	321	358	396	288	288	144
987	932	870	318	356	388	276	290	150
992	932	870	318	356	392	284	284	148
996	930	868	321	358	390	280	286	152
993	936	864	324	360	390	280	286	152
986	926	874	314	362	388	276	290	150
1005	930	868	321	358	392	284	284	148
1010	932	870	318	356	396	288	288	144
1002	936	864	324	356	392	284	284	148
1000	926	874	314	358	390	280	286	152
995	930	868	321	362	388	276	290	150
998	932	870	318	360	392	284	284	148

Let's carry out correlation-regression analysis to describe the dependence of the index of innovation, obtained as a result of experiments, on the content of substances in it (Table 1). Taking the factors affecting the index as factor signs, we obtain the main one as the resulting sign and determine the multiple regression equation. We look for the dependence of index factors (Y) on many factors in the form of linear multiple regression: $\hat{Y} = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 + a_5x_5 + a_6x_6 + a_7x_7 + a_8x_8$,

where- regression coefficients determined by the least squares method; factor signs: x1- factor, x2- factor, x3- factor, x4- factor, x5- factor x6- factor x7- factor x8- factor. Estimating the equation parameters using the least squares method, we define the regression equation as follows:
$$\hat{Y} = 2383,331 - 1,07x_1 - 0,99x_2 - 0,18x_3 - 0,54x_4 + 0,369x_5 + 1,11x_6 + 0,67x_7 + 0,505x_8$$

Table 2. Regression analysis protocol.

CONCLUSION	
Regression statistics	
Multiple R	0,6989
R-squared	0,48846
Normalised R-squared	0,1164

Standard error	4,9220
Observations	20

Analysis of variance

	df	*SS*	*MS*	*F*	*Significance of F*
Regression	8	254,4618	31,80772	1,312947	0,32967
Residue	11	266,4882	24,2262		
Total	19	520,95			

	Coefficients	*Standard error*	*t-statistics*	*P-value*	*Bottom 95 per cent*	*The top 95 per cent*	*Bottom 95.0%*	*Upper 95.0%*
Y-intersection	2383,33	2372,092	1,004738	0,336613	-2837,61	7604,27	-2837,61	7604,27
Variable X 1	-1,07	0,868556	-1,23377	0,242999	-2,98328	0,840077	-2,98328	0,840077
Variable X 2	-0,99	1,388218	-0,71378	0,490234	-4,04632	2,06457	-4,04632	2,06457
Variable X 3	-0,18	0,910235	-0,20286	0,84295	-2,18806	1,818767	-2,18806	1,818767
Variable X 4	-0,54	0,777749	-0,6935	0,502377	-2,25118	1,172445	-2,25118	1,172445
Variable X 5	0,369	0,406198	0,909054	0,382807	-0,52478	1,263293	-0,52478	1,263293
Variable X 6	1,11	0,915111	1,212989	0,25054	-0,90413	3,124166	-0,90413	3,124166
Variable X 7	0,67	0,925318	0,726701	0,482587	-1,36418	2,70904	-1,36418	2,70904
Variable X 8	0,505	1,172913	0,430234	0,675333	-2,07694	3,08619	-2,07694	3,08619

The difference between the experimental values and calculated theoretical values of the resulting trait, given in the table, determines the error of approximation of the constructed model. The average approximation error of linear multiple regression is defined as:

$$A = \frac{1}{n}\sum_{k=0}^{n}\left|\frac{Y - Y}{Y}\right| * 100\%$$

This value means that the constructed model has a good quality, that is, the selected regression equation describes the provided statistical data with a marginal error. We check the quality of the model by Fisher's criterion. This criterion is used to test the hypothesis that the total variance is equal to zero, i.e. it is assumed that the nature of the dependence is random. Since the calculated value F(1,3129) > Fkr(0,3297) is greater than the tabulated value, the linear multiple regression equation is considered adequate, and the hypothesis about the random nature of this dependence is rejected.

From the results found, we see that the correlation coefficient is 0.6989, which indicates that there is a direct relationship between the resulting label (Y) and the factors obtained. This indicates that since the value is less than 0.7, the relationship between the selected indicators is weak. The coefficient of determination is 48.8% which means that the resultant mark (y) depends on this value from the factors obtained. And the remaining 100-48.8 = 51.2% shows that the resulting mark depends on other factors not considered in the model, including the innovation index.

Part of the experimental data in Table 1 acquires a constant value in the calculation of the innovation index X1 - digitalisation of the economy, x2 - human potential factor.

Table 3. Experimental data modified during the technological process.

Innovation Index, Y	, X1	, X2
1000	396	279
1010	397	280,5
1005	396,5	281,5
1020	395	282
1015	394,5	283
1001	393	284
994	392	285
1005	391	286
1000	390	287
997	389	288

According to Table 3, we construct a nonlinear multiple regression model as follows: $Y = a + b_1x_1 + b_2x_2 + b_3x_1x_2 + b_4x_1^2 + b_5x_2^2$

The regression analysis estimated the equation parameters and the regression equation was defined as follows: $\hat{Y} = -6726945 + 23538,02x_1 + 14717,84x_2 - 27,37x_1x_2 - 20,0056x_1^2 - 6,91x_2^2$

Table 4. Regression analysis protocol.

CONCLUSION

Regression statistics	
Multiple R	0,842123
R-squared	0,709171
Normalised R-squared	0,345635
Standard error	6,605421
Observations	10

Analysis of variance

	df	*SS*	*MS*	*F*	*Significance of F*
Regression	5	425,5737	85,11473	1,95076	0,268544
Residue	4	174,5263	43,63159		
Total	9	600,1			

	Coefficients	*Standard error*	*t-statistics*	*P-value*	*Bottom 95 per cent*	*The top 95 per cent*	*Bottom 95.0%*	*Upper 95.0%*
Y- Y-intersection	-6726945	3232633	-2,08095	0,105909	-1,6E+07	2248283	-1,6E+07	2248283
Variable X 1	23538,02	11361,58	2,071721	0,107021	-8006,78	55082,82	-8006,78	55082,82
Variable X 2	14717,84	7433,239	1,980003	0,118801	-5920,14	35355,82	-5920,14	35355,82
Variable X 3	-20,0056	9,77233	-2,04717	0,110043	-47,138	7,126718	-47,138	7,126718
Variable X 4	-6,90794	4,568374	-1,51212	0,205043	-19,5918	5,775904	-19,5918	5,775904
Variable X 5	-27,3747	13,27224	-2,06255	0,108139	-64,2243	9,474932	-64,2243	9,474932

The following scientific methods are used in the presented scientific article: deductive method used to analyse the commercialisation of innovations in order to determine the evaluation of their application; method of scientific analysis aimed at studying the theoretical foundations of commercialisation of innovations with the definition of the phenomena that determine the mechanism of commercialisation of innovations. its application [21].

The synthesis method allows us to obtain extensive research results, form and generalise conclusions about current trends and phenomena in the theories of innovation commercialisation. The graphical method and abstract-logical method are used.

In addition, the work uses scientific provisions on innovation planning, analysis of innovation processes, as well as general scientific methods of cognition: complex and abstract-logical. Literature sources were searched using keywords related to the commercialisation process in three main databases: Scopus (sciencedirect.com), Clarifying Analytics (webofknowledge.com) and RINC (elibrary.ru). As part of this process, more than 100 articles by experts specialising in the commercialisation of scientific developments and the implementation of effective innovation activities in industrial enterprises were analysed. The implications of idempotent addition of information (knowledge) in economic equilibrium models are analysed. Kazakhstan is in 83rd place in the Global Innovation Index - 2022 based on 2021 data. The study evaluated 132 countries.

IV. DISCUSSION

Kazakhstan in the rating 2022 with a score of 24.7 points is located in 83rd place between Uzbekistan and Albania. According to the results of the 2022 ranking, Kazakhstan in terms of three factors (institutions, human capital and research, infrastructure) is within the 3rd quartile (places 34-66), in terms of the level of market development, business and results in the field of knowledge and technology - in the 2nd quartile (places 67-99), and on the results of creative activity - in the 1st quartile (places 100-132).

Minor improvements in Kazakhstan are noted in the factors "Human Capital and Research", "Business Development" and "Development of Technology and Knowledge Economy".

In the "Human Capital and Research" factor, Kazakhstan moved up 6 positions from 66th to 60th place. This factor takes into account such indicators as education expenditure, government funding per secondary school student, school life expectancy, graduates in science and technology, and gross expenditure on R&D. Kazakhstan ranks high in the following indicators: student-teacher ratio in secondary school (8.3) - 12th place, enrolment in higher education (70.7 per cent) - 33rd place and the average score of the top three universities in the country (34.7 points) - 36th place.

In the "Business Development" factor, Kazakhstan moved up 10 points from 78th to 68th place. The country's strength in terms of this factor is the significant share of employed women with academic degrees (20.7% of total employment) - 31st place in the ranking.

In the factor "Development of Technology and Knowledge Economy" Kazakhstan moved up 5 points from 86th to 81st place due to significant improvements in the sub-factors "Knowledge Impact" (+17 points) and "Knowledge Dissemination" (+20 points). Kazakhstan occupies a competitive position in the context of this factor by two indicators: the share of resident utility model applications filed with the national patent office (1.6% of GDP) - 14th place and the growth rate of real GDP per employed person, on average over the last three years (2.2%) - 31st place.

It is worth noting that in the current ranking Doing Business indicators have been replaced by alternative indicators, which led to a decrease in positions. At the same time, one of the sources was the World Economic Forum (WEF), which is irrelevant, as the latest rating is formed based on the results of 2019.

Thus, the decline in Kazakhstan's position on the sub-factor "Business Environment" (- 26 points) is explained by its low position on the WEF survey indicator (the government's provision of a stable policy for doing business - 93rd place).

In the Trade, Diversification and Market Scale sub-factor, there was a decrease in the following indicators: "Weighted average tariff rate applied" from 57th to 61st place and "Scale of domestic market" from 40th to 41st place. It should also be noted that the indicator "Ease of obtaining credit" was replaced by "Finance for startups and skylaps", which also contributed to the decrease in the country's position in the sub-factor "Credit". In addition, a small share of investment deals with venture capital and a low number of venture capital recipients can be highlighted as weaknesses.

Weak positions by the results of creative activity in Kazakhstan (118th place). Thus, there is a decline in the position for creative goods and services, in particular, the number of national feature films made (per million population aged 15-69 years)" from 38th to 73rd place.

In the context of the sub-factor "Intangible Assets" there is a decrease in the country's position in the following indicators: "Share of resident applications for trademarks" from 87th to 92nd place, and "Share of resident applications for industrial designs" from 103rd to 107th place.

Overall, the 2022 survey results show that the Global Innovation Landscape is changing - both among the top 25 innovative economies and more broadly across the index as a whole and in ranking tables by income group or region.

The most significant of these changes are: - significant shifts in the ranking of the top 15 innovation economies, with the US, Singapore, Germany and China (ahead of France) strengthening their positions, and Canada returning to the top 15 due to improved innovation performance; - continued strong progress by the fast-growing engines of innovation - Turkey, India and to some extent the Islamic Republic of Iran - while Vietnam and the Philippines are slowing down; - early signs of the innovation potential of Indonesia, Uzbekistan and Pakistan, which have all seen their innovation potential increase; - and - the first signs of the innovation potential of Indonesia, Uzbekistan and Pakistan.

V. CONCLUSIONS

Kazakhstan's lag in the Global Innovation Index is primarily due to low investment in R&D, limited access to funding and technology, and challenges in education and global market integration. To address these issues, the country should focus on strengthening research, supporting SMEs, enhancing education, fostering international cooperation, and building an innovation-friendly ecosystem. Our innovation lies in creating a mathematical model for optimizing innovation ecosystems, integrating factors such as R&D investment, technology diffusion, and market access. Using differential equations and dynamic system modeling, we analyze how investments and policies influence innovation growth over time. For future research, we recommend expanding the model with real-world data from Kazakhstan's industries and exploring policy simulations to identify the most effective strategies for boosting the country’s innovation index.

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Author Contribution

All authors made an equal contribution to the development and planning of the study.

Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data are available from the authors upon request.

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