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© **Esimkhan G.E.¹, Rakhimberdinova M.U.², Kabieva A.^{3*}, 2026.**¹ Akhmet Baitursynuly Kostanay Regional University, Kostanay, Kazakhstan;² D. Serikbayev East Kazakhstan Technical University,
Ust-Kamenogorsk, Kazakhstan;³ K. Kulazhanov Kazakhstan Technological University, Astana, Kazakhstan.
E-mail: asem_kt_1985@mail.ru

SUSTAINABLE DEVELOPMENT OF THE AGRO-INDUSTRIAL COMPLEX THROUGH INNOVATION AND DIGITAL TECHNOLOGIES

Esimkhan Guldana — PhD, Assistant Professor, Akhmet Baitursynuly Kostanay Regional University, Kostanay, Kazakhstan,E-mail: guldana_esimhan@mail.ru, ORCID: <https://orcid.org/0000-0002-0095-3018>;**Rakhimberdinova Madina** — PhD, Professor, D. Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk, Kazakhstan,E-mail: MRakhimberdinova@edu.ektu.kz, ORCID: <https://orcid.org/0000-0001-9009-8686>;**Kabiyeva Assem** — PhD, Assistant Professor, Department of Finance and Accounting, K. Kulazhanov Kazakhstan Technological University, Astana, Kazakhstan,E-mail: asem_kt_1985@mail.ru, ORCID: <https://orcid.org/0000-0002-8465-6984>.

Abstract. Sustainable development of the agro-industrial complex requires aligning production efficiency, natural resource conservation, and access to economic opportunities. This study identifies conditions for effective use of innovations and digital technologies and proposes an assessment model for Kazakhstan. The methods comprise an analytical literature review, document analysis, and descriptive processing of official statistics. The quantitative evidence covers investment in agriculture, forestry, and fishing in 2024–2025 and adoption of water-saving technologies in 2023–2025. Investment increased from KZT 737.9 billion to KZT 1,153.6 billion, or 56.3% in current prices, with volume growth of 51.8%. The share of own funds fell from 59.19% to 54.61%, but it remained the leading financing source. The area covered by water-saving systems increased from 237.1 to 543.5 thousand hectares, a 129.2% increase. These indicators describe modernisation conditions and technical coverage but do not establish a causal effect of digitalisation. An analytical model links observation, data validation, decision-making, implementation, and outcome measurement. The proposed indicators cover economic, environmental, social, and organisational

dimensions. Practical applications involve assessing total ownership costs, resource intensity, accessibility of adoption, and service reliability. Regional adaptation, cooperative equipment use, and information system interoperability are justified. The contribution is the distinction between digital equipment deployment and sustainable operational outcomes. The absence of farm microdata and a comparable control group limits the study. Further validation requires observations across several production seasons and assessment of costs, resources, and outcomes before and after technology adoption.

Keywords: agro-industrial complex; sustainable development; innovation; digital technology; resource efficiency; precision agriculture; Kazakhstan

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¹ Ахмет Байтұрсынұлы атындағы Қостанай өңірлік университеті,
Қостанай, Қазақстан;

² Д. Серікбаев атындағы Шығыс Қазақстан техникалық университеті,
Өскемен, Қазақстан;

³ Қ. Құлажанов атындағы Қазақстан технологиялық университеті,
Астана, Қазақстан.

E-mail: asem_kt_1985@mail.ru

ИННОВАЦИЯЛАР МЕН ЦИФРЛЫҚ ТЕХНОЛОГИЯЛАР НЕГІЗІНДЕ АГРОӨНЕРКӘСІПТІК КЕШЕННІҢ ТҰРАҚТЫ ДАМУЫ

Есімхан Гүлдана — философия докторы (PhD), ассистент-профессор, Ахмет Байтұрсынұлы атындағы Қостанай өңірлік университеті, Қостанай, Қазақстан,
E-mail: guldana_esimhan@mail.ru, <https://orcid.org/0000-0002-0095-3018>;

Рахимбердинова Мадина — философия докторы (PhD), профессор, Д. Серікбаев атындағы Шығыс Қазақстан техникалық университеті, Өскемен, Қазақстан,
E-mail: MRakhimberdinova@edu.ektu.kz, <https://orcid.org/0000-0001-9009-8686>;

Кабиева Асем — философия докторы (PhD), «Қаржы және есеп» кафедрасының ассистент-профессоры, Қ. Құлажанов атындағы Қазақстан технологиялық университеті, Астана, Қазақстан,

E-mail: asem_kt_1985@mail.ru, <https://orcid.org/0000-0002-8465-6984>.

Аннотация. Агроөнеркәсіптік кешеннің тұрақты дамуы өндірістік тиімділікті, табиғи ресурстарды сақтауды және экономикалық мүмкіндіктердің қолжетімділігін үйлестіруді талап етеді. Зерттеудің мақсаты - инновациялар мен цифрлық технологияларды нәтижелі қолдану шарттарын анықтау және олардың үлесін Қазақстан жағдайында бағалау моделін ұсыну. Халықаралық әдебиетке талдамалық шолу, құжаттарды талдау және ресми

статистиканы сипаттамалық өңдеу қолданылды. Сандық негізге ауыл, орман және балық шаруашылығына 2024–2025 жылдары салынған инвестициялар мен 2023–2025 жылдардағы су үнемдеу технологияларының қолданылуы енгізілді. Инвестициялар ағымдағы бағамен 737,9 млрд теңгеден 1153,6 млрд теңгеге дейін, яғни 56,3% өсті, ал нақты көлем өсімі 51,8% болды. Меншікті қаражаттың үлесі 59,19%-дан 54,61%-ға дейін төмендегенімен, негізгі қаржыландыру көзі болып қалды. Су үнемдеу жүйелері қолданылатын аумақ 237,1 мың гектардан 543,5 мың гектарға дейін, яғни 129,2% артты. Бұл көрсеткіштер жаңғырту шарттары мен техникалық қамтуды сипаттайды, бірақ цифрландырудың себептік әсерін дәлелдемейді. Бақылауды, деректерді тексеруді, шешім қабылдауды, орындауды және нәтижені өлшеуді байланыстыратын талдамалық модель ұсынылды. Индикаторлар жүйесі экономикалық, экологиялық, әлеуметтік және ұйымдастырушылық өлшемдерді қамтиды. Практикалық құндылық инновациялық жобаларды иеленудің толық құнына, ресурс сыйымдылығына, игеру қолжетімділігіне және қызмет көрсету сенімділігіне бағдарлаудан тұрады. Өңірлік бейімдеу, жабдықты кооперациялық пайдалану және ақпараттық жүйелердің үйлесімділігі негізделді. Ғылыми үлес цифрлық жарақтандыру мен тұрақты шаруашылық нәтижесін ажыратуға байланысты. Зерттеудің шектеуі шаруашылықтардың микродеректері мен салыстырмалы бақылау тобының болмауына негізделеді. Модельді әрі қарай тексеру бірнеше өндірістік маусымдағы бақылауды және технология енгізілгенге дейінгі және кейінгі шығындарды, ресурстарды, нәтижелерді бағалауды қажет етеді.

Түйін сөздер: агроөнеркәсіптік кешен; тұрақты даму; инновация; цифрлық технология; ресурс тиімділігі; дәлме-дәл егіншілік; Қазақстан

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¹ Костанайский региональный университет имени Ахмет Байтұрсынұлы, Костанай, Казахстан;

² Восточно-Казахстанский технический университет имени Д. Серикбаева, Усть-Каменогорск, Казахстан;

³ Казахстанский технологический университет имени К. Кулажанова, Астана, Казахстан.

E-mail: asem_kt_1985@mail.ru

УСТОЙЧИВОЕ РАЗВИТИЕ АГРОПРОМЫШЛЕННОГО КОМПЛЕКСА НА ОСНОВЕ ИННОВАЦИЙ И ЦИФРОВЫХ ТЕХНОЛОГИЙ

Есімхан Гүлдана — доктор философии (PhD), ассистент-профессор, Костанайский региональный университет имени Ахмет Байтұрсынұлы, Костанай, Казахстан, E-mail: guldana_esimhan@mail.ru, <https://orcid.org/0000-0002-0095-3018>;

Рахимбердинова Мадина — доктор философии (PhD), профессор, Восточно-Казахстанский технический университет имени Д. Серикбаева, Усть-Каменогорск, Казахстан,

E-mail: MRakhimberdinova@edu.ektu.kz; <https://orcid.org/0000-0001-9009-8686>.

Кабиева Асем — доктор философии (PhD), ассистент-профессор кафедры «Финансы и учет», Казахстанский технологический университет имени К. Кулажанова, Астана, Казахстан,
E-mail: asem_kt_1985@mail.ru; <https://orcid.org/0000-0002-8465-6984>.

Аннотация. Устойчивое развитие агропромышленного комплекса требует согласования производственной эффективности, сохранения природных ресурсов и доступности экономических возможностей. Цель исследования — определить условия результативного применения инноваций и цифровых технологий и предложить модель оценки их вклада применительно к Казахстану. Использованы аналитический обзор международной литературы, документальный анализ и описательная обработка официальной статистики. Количественная база охватывает инвестиции в сельское, лесное и рыбное хозяйство за 2024–2025 годы и применение водосберегающих технологий за 2023–2025 годы. Инвестиции увеличились с 737,9 до 1153,6 млрд тенге, или на 56,3% в текущих ценах, при приросте физического объёма на 51,8%. Доля собственных средств снизилась с 59,19 до 54,61%, сохранив ведущее положение. Площадь применения водосберегающих систем выросла с 237,1 до 543,5 тыс. га, или на 129,2%. Эти показатели характеризуют условия и технический охват модернизации, но не доказывают причинного эффекта цифровизации. Предложена аналитическая модель, связывающая наблюдение, проверку данных, принятие решения, исполнение и измерение результата. Система индикаторов включает экономическое, экологическое, социальное и организационное измерения. Практическая ценность состоит в ориентации инновационных проектов на полную стоимость владения, ресурсную интенсивность, доступность освоения и надёжность обслуживания. Обоснованы региональная адаптация, кооперационное использование оборудования и совместимость информационных систем. Научный вклад заключается в разграничении цифрового оснащения и устойчивого хозяйственного результата. Ограничение исследования связано с отсутствием микроданных хозяйств и сопоставимой контрольной группы. Дальнейшая проверка модели требует наблюдений в нескольких производственных сезонах и оценки затрат, ресурсов и результатов до и после внедрения технологий.

Ключевые слова: агропромышленный комплекс; устойчивое развитие; инновация; цифровая технология; ресурсоэффективность; точное земледелие; Казахстан

Introduction. Sustainable development of the agro-industrial complex presupposes increasing value creation while preserving the natural basis of production, food accessibility, and employment opportunities for the rural population. This approach requires considering not only output volume but also resource intensity, supply reliability, farm financial viability, and the distribution of modernisation results. For Kazakhstan, this approach is especially important

due to the spatial heterogeneity of production, the dependence of certain territories on irrigation, and the variability of natural conditions. Innovations and digital technologies expand the tools for managing these processes, but they deliver sustainable results only when production, economic, and institutional decisions are coordinated.

Technological modernisation is changing how soil conditions are monitored, water is used, procurement is organised, and products are distributed. Sensors, satellite imagery, positioning systems, electronic traceability, and analytical platforms enable decisions based on more detailed information. At the same time, developing breeding, agricultural technology, processing, and production cooperation creates a material foundation for using digital tools. Their interconnection is fundamental: obtaining data does not eliminate the irrigation network's insufficient capacity, and upgrading equipment without qualified maintenance does not ensure long-term effectiveness. Consequently, digitalisation should be considered as part of comprehensive innovative development.

In Kazakhstan, conditions are emerging to expand such modernisation. Official annual tables show an increase in fixed-capital investments in agriculture, forestry, and fisheries from 737.9 billion tenge in 2024 to 1,153.6 billion tenge in 2025 (BNS, 2025, 2026a). At the same time, the use of water-saving systems is expanding, and government agencies identify the integration of sectoral information resources as a direction for further development. However, total investments include various types of assets and do not directly reflect the costs of digitalisation. For research purposes, it is necessary to distinguish between the resource prerequisites for modernisation, the actual application of technologies, and the measured results of their use.

The article aims to identify the conditions under which innovations and digital technologies contribute to the sustainable development of the agro-industrial complex and to propose a model for assessing the results of their implementation in relation to Kazakhstan. The research question is what organisational and financial mechanisms transform technological equipment into increased productivity, reduced resource intensity, and expanded access to economic opportunities. The analysis focuses on the relationship between the production solution, the information infrastructure, and the system of indicators that makes it possible to verify the achieved effect.

To achieve this goal, international studies have been systematised, official investment indicators for 2024–2025 have been examined, and the dynamics of applying water-saving technologies for 2023–2025 have been analysed. Based on this, the authors developed an analytical management model and proposed a system of economic, environmental, social, and organisational indicators. The scientific contribution lies in distinguishing between digital equipment and sustainable results, as well as in linking individual technologies to verifiable management tasks. The work presents a descriptive and methodological study; it does not establish a causal effect of digitalisation on the national output of agricultural products.

Literature review. International studies of digital agriculture show that the

technological effect arises from using information to make production decisions. Wolfert et al. (2017) examine big data in the context of farm management and participants' interactions in the agri-food chain. This approach makes it possible to separate the accumulation of digital records from changes in work technology. For sustainable development, the quality of the original information, the timeliness of analysis, and the ability to implement the resulting recommendations are important. The presence of a platform or sensor is an intermediate result of implementation, not an independent proof of increased productivity.

Klerkx et al. (2019) expand the analysis to include the social and organisational aspects of digital agriculture. Introducing new solutions changes workers' competencies, farmers' interactions with service providers, and the distribution of control over data. For Kazakhstan, this perspective matters when assessing differences between large farms and small producers. With the same technical offering, access to funding, personnel, and service support may determine unequal ability to use the technology. Therefore, spreading digital tools requires analysing the conditions for adoption, not just the quantity of equipment supplied.

Rose et al. (2021) link the development of agriculture in the new technological generation to people's interests, production, and the environment. Their approach emphasises the need to assess the social impact of innovations alongside production efficiency. Automation can improve working conditions and operational accuracy, but it also changes skill requirements and access to jobs. Therefore, the social component of sustainability must be included in the modernisation project before scaling up, including training, organising consulting support, and involving workers in changing production processes.

Benos et al. (2021) systematise the application of machine learning in crop, water, soil, and livestock management. The potential of algorithms is linked to processing heterogeneous data and predicting the condition of production facilities. However, transferring a model to another agro-climatic zone requires verification of its quality. An erroneous recommendation regarding irrigation or crop treatment can lead to production and environmental losses. Therefore, assess analytical accuracy and economic utility separately, and complement algorithm use with agronomic expertise and testing on new data.

The FAO reports (2021, 2022) examine the sustainability of agri-food systems and the conditions for inclusive automation. This literature links technological development to infrastructure, skills, and capital availability. The FAO (2023, 2024) supplements the assessment by considering the broader economic, social and environmental impacts of production. For the present work, these approaches mean that the savings of an individual resource should be checked along with changes in other costs and impacts. A decrease in water supply, for example, is not necessarily accompanied by a decrease in energy consumption if the new system requires additional pressure and pumping equipment.

Schroeder et al. (2021) consider the digital transformation of the entire agri-food system, including markets, finance, and data management. The OECD (2025) and

the OECD and FAO (2025) reveal the role of agricultural policy and the prospects for market development. The IPCC (2022) and the World Bank Group (2022) present the climate context. Together, these studies support the comprehensive nature of modernisation but do not provide a ready-made efficiency coefficient for Kazakhstani farms. The research gap is the lack of a link between aggregated indicators of technological development and the verification of results at the economy and production-chain levels.

Materials and basic methods. The study combines an analytical review of the literature, documentary analysis and descriptive processing of official data. The study includes 20 sources: peer-reviewed research on digital agriculture, international reports, statistical tables, and documents from government agencies in Kazakhstan. The selection is targeted and is based on compliance with three issues: the mechanism of technological impact, the conditions for mastering innovations and measuring sustainable results. The work does not appear to be a systematic review following the PRISMA protocol and does not provide exhaustive coverage of the literature. We used verifiable publications with available bibliographic information and DOIs for journal articles.

The quantitative base includes annual investment tables for 2024 and 2025, published in 2025 and 2026, respectively (BNS, 2025, 2026a). The section "Agriculture, forestry and fisheries" has been selected. It characterises the primary manufacturing sector and does not cover the entire intersectoral agro-industrial complex, including processing, logistics and other activities. Monetary values have been transferred from thousands of tenge to billions of tenge. The categories of funding sources are checked for compliance with the overall total. Budget funds combine the republican and local levels; non-resident funds are not added separately if they are already included in other borrowed funds.

The calculation of the nominal rate of change of investments and the share of financing sources is applied. The published volume index is used to characterise changes in comparable prices and is considered separately from nominal growth. According to the current version of industry statistics, the gross output of agriculture, forestry and fisheries in 2025 amounted to 9.77 trillion tenge, and the physical volume index was 105.9% (BNS, 2026b). These indicators are used as a context. Gross output is not equal to value added, and its increase cannot be directly attributed to the introduction of digital technologies.

The updated data on wheat harvest in weight after refinement (BNS, 2026c) illustrate raw material variability. The indicators do not mix with the operational estimates in the initial weight. The dynamics of water-saving technologies for 2023-2025 are taken from the message of the Ministry of Water Resources and Irrigation (2026). This is an administrative description of the area where the equipment is used; it does not show the proportion of farms with digital irrigation control. The figures for the incomplete year 2026 are not included in the annual comparison. Documents and source versions have been verified as of October 12, 2026.

The methodological model combines four dimensions of sustainability: economic, environmental, social and organizational. The economic dimension characterises value created and costs; the environmental dimension characterises the use of water, energy, and other resources; the social dimension characterises working conditions and the availability of participation in modernisation; the organisational dimension characterises data quality, the reliability of procedures, and the ability to support technology. An object of management, a possible tool, a result indicator, and an interpretation condition are defined for each direction. The weights and the integral rating are not calculated because there are no grounds for empirical calibration.

When preparing the project, ChatGPT (GPT-6) was used to search for sources, organise the material, and generate preliminary text, calculations, and visualisations. The statistical values were compared with the source tables during project preparation. The final substantive review and confirmation of the manuscript by the authors must precede submission. The main limitations of the study are the lack of farm-level microdata, the lack of measured digitalisation costs, and the lack of comparable control-group results. Therefore, the conclusions relate to the conditions and mechanisms of modernisation, not to a causal assessment of its effectiveness.

Results. Official statistics show an expansion of the investment base in the primary sector. Over the period from 2024 to 2025, investments in fixed capital increased by 56.3% at current prices. The published physical volume index for 2025 is 151.8%, meaning growth at comparable prices is 51.8%. This difference reflects the need to separate changes in monetary value from real investment volume. At the same time, the investment upswing does not reveal the composition of the assets being acquired. To determine the digital component, a separate classification of costs for sensors, software, communication, automation, and related services is required.

Table 1 — Investments in agriculture, forestry, and fisheries in Kazakhstan

A source	2024, billion tenge	2024, %	2025, billion tenge	2025, %
Budget funds	1,547	0,21	11,495	1,00
Own funds	436,723	59,19	629,986	54,61
Bank loans	34,930	4,73	71,048	6,16
Other borrowed funds	264,690	35,87	441,069	38,23
Total	737,891	100,00	1 153,599	100,00
Note: BNS calculations (2025, 2026a). Current prices. The budget funds combine the republican and local levels. These are investments from the primary sector, not the entire intersectoral agro-industrial complex; a separate share of digital spending has not been measured.				

Own funds retained their leading role in financing. Their volume increased from 436.7 to 630.0 billion tenge, but their share in the total decreased from 59.19 to 54.61%. At the same time, bank loans increased from 34.9 to 71.0 billion tenge, and other borrowed funds — from 264.7 to 441.1 billion tenge. This structure

shows that investment growth is linked to several sources of capital. The category of other borrowed funds does not automatically identify a specific financial instrument, and direct budget financing does not reflect all forms of government support.

For an innovative project, the financial structure has an independent meaning. Equipment purchases create upfront costs, while the economic effect emerges in subsequent production cycles. Additional costs include setup, training, communication, maintenance, and replacement of individual components. Therefore, the investment assessment should take into account the total cost of ownership, not just the delivery price. Leveraged financing can accelerate implementation, but increases the requirements for the timing of the result and sufficient cash flow. An increase in total investment alone does not establish the financial viability of an individual digital project. According to updated statistics, wheat harvest increased from 12.11 million tons in 2023 to 18.58 million tons in 2024 and 19.33 million tons in 2025. This significant inter-annual shift underscores the need to account for weather, technology, and crop structure when assessing modernisation outcomes. Digital monitoring can improve the timeliness of management responses, but it does not eliminate natural variability. When analysing the farm, indicators should be compared with the conditions of a particular season, and yield increases should not be automatically interpreted as an effect of the information system.

Water-saving technologies represent a direction in which modernisation is associated with a measurable resource benefit. The area of their use increased from 237.1 thousand hectares in 2023 to 543.5 thousand hectares in 2025, or by 129.2%. The absolute increase amounted to 306.4 thousand hectares. The dynamics demonstrate the expansion of technical coverage and create the basis for more accurate management of water supply. However, drip or sprinkler irrigation equipment does not necessarily include digital sensors and automatic controls; these components must be accounted for separately.

Table 2 — Application of water-saving technologies in Kazakhstan

Year	Area of application, thousand hectares	Growth compared to the previous year, in thousands of hectares.
2023	237,1	—
2024	389,9	152,8
2025	543,5	153,6

Note: Compiled by the Ministry of Water Resources and Irrigation (2026). Annual figures for 2023-2025; incomplete data for 2026 are excluded. The area of application of irrigation systems is not equal to the area of digital irrigation control.

The area of application is an indicator of the spread of the technology, but it is not a complete measure of water efficiency. The farm needs data on water supply, weather, soil moisture, crop, and produced output. In addition to water consumption per hectare, it is necessary to assess the consumption per unit of

output, since changes in yield affect the overall resource intensity. At the water basin level, it is necessary to account for the distribution of water among users and the possible expansion of the irrigated area. Improving the efficiency of an individual plot does not guarantee a reduction in total consumption when the scale of production increases.

In this regard, combining agrotechnical and digital innovations offers a clearer mechanism of impact than implementing a platform on its own. A properly functioning irrigation infrastructure makes it possible to regulate supply; sensors and forecasts provide information about the need, and the control system switches to irrigation mode. The result check completes the process: water supply, crop yield, and costs are measured. If even one link is missing, the technological equipment may not lead to the expected change in farming practices. This provision defines the structure of the proposed model.

The model includes interrelated production and organisational components. The production part begins with monitoring resources and objects: the field, the herd, inventory, processing, and logistics. The organisational part defines data access, responsibility distribution, the budget, and the ability to implement the solution. Analytics compares observations with the farm's objectives, after which it forms an action and measures the result. Feedback allows for refining the algorithm and the production process. Figure 1 presents the proposed management architecture; its effectiveness still needs to be tested using data from enterprises.

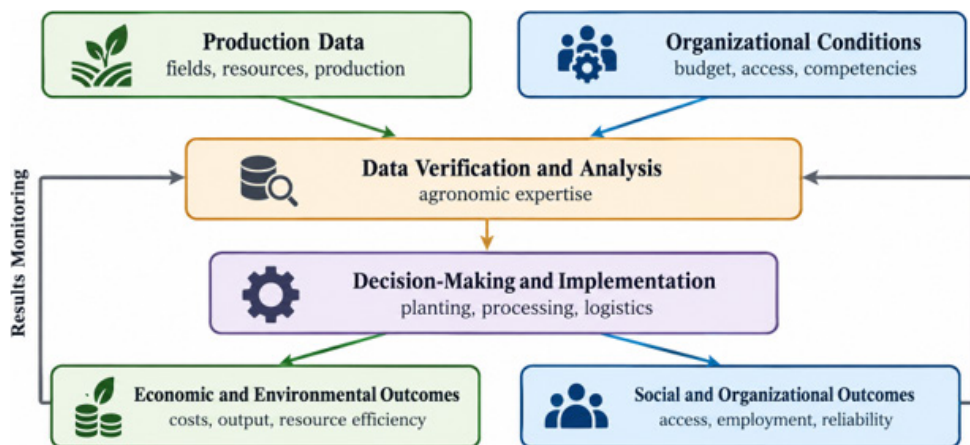


Figure 1 — Analytical model of the transition from data to a sustainable result

Note: the proposed management architecture. Feedback links result measurement with re-examining data and solutions. Empirical validation of the model was not performed in the present study.

The difference between the model and the approach based on the number of digital solutions lies in the mandatory transition to a specific action. Satellite

detection of field heterogeneity is valuable if it is used for surveying, differentiated resource application, or changing agricultural practices. Predicting herd disease requires a verification procedure and a veterinary decision. Information about stocks should influence the procurement and logistics schedule. Therefore, the unit of assessment becomes a production task, for which the initial state, the decision made, and the observed result can be compared.

The quality of data in this architecture is a production condition. Errors in identifying the plot, measurement time, or consumption units can lead to incorrect recommendations. General reference books, recording the origin of the record, and error correction rules are required. For algorithmic solutions, it is also necessary to verify data not used during setup and to assess the consequences of an erroneous action. An agronomist or other responsible specialist should be able to verify the recommendation and, if necessary, cancel it. This organization reduces the risk of automatically reproducing incorrect data.

The proposed system of indicators links the technology to four dimensions of sustainability. Table 3 presents the indicators that can be used in a farm, cooperative, or support project. They represent a methodological proposal and do not indicate national values that have already been achieved. For comparison, you need a consistent definition of the process boundaries, period, and unit of output. It is especially important to take into account the costs of implementation and maintenance; otherwise, the observed reduction in production costs may be accompanied by an increase in the overall cost of operations.

Table 3 — Proposed indicators of sustainable results

Measurement	The tool	Indicator	Evaluation condition
Economic	Precision agriculture; inventory management	Full cost; product losses; productivity	Include maintenance and cost of capital
Environmental	Irrigation management; variable rate application	Water and energy per unit of output; absolute consumption	Consider the culture, season, and boundaries of the process
Social	Service access; training; labour automation	Ease of adoption; practical qualification; working conditions	Compare producer and employee groups
Organizational	Compatible systems; verification and backup	Data completeness; recovery time; export capability	Verify data origin and responsibility
Note: this methodological proposal is based on the studies reviewed.			

Economic assessment should include changes in productivity, product losses, and total cost. When using precision agriculture, the study examines processing costs, product yield, and equipment maintenance costs. In processing and storage, quality losses, downtime, and inventory turnover duration are important. Sales through a digital platform are assessed based on revenue after commission, delivery, and returns. This approach allows comparison of new and existing production methods on the same economic basis, without substituting a sustainable outcome with an increase in digital transactions.



Environmental assessment requires several interrelated metrics. It considers water, energy, nutrients, soil condition, and waste. A reduction in fertiliser consumption should be accompanied by a check of crop yields and the balance of plant nutrition, and energy efficiency should account for all significant operations in the production cycle. If a project changes the output volume, it is necessary to simultaneously show the absolute use of the resource and the use per unit of output. This makes it possible to identify situations where specific efficiency increases, but the overall load on the natural environment grows.

The social outcome is characterised by technology availability, changes in working conditions, and opportunities for skill development. For a small farm, service clarity, subscription cost, and access to support in case of failures are important. Training is evaluated not only by the number of participants but also by the ability to perform production activities after completing the course. Differences in access between groups of workers and producers should be taken into account. Automating hazardous or physically demanding operations can improve working conditions, but releasing workers requires adaptation measures and preparation for new tasks.

Organisational indicators reflect the system's ability to sustain itself after the pilot phase. These include data completeness, the proportion of corrected errors, recovery time after a failure, and the availability of information export. A data transfer function matters when changing suppliers and reduces dependence on a closed platform. These indicators complement the financial assessment: an inexpensive service may create long-term limitations if the data cannot be used in other systems. Therefore, the supplier's compatibility and liability requirements must be taken into account before signing the contract.

Digital tools must be complemented by innovations in breeding, agricultural technology, processing, and the organisation of the production chain. A resilient variety, an appropriate soil cultivation regime, and a reliable storage system influence outcomes through material technology, while monitoring helps select the conditions for their application. For the farm, sequential diagnostics are useful: first, the main limitation is identified, then a production solution and an information tool to support it are selected. If losses are caused by insufficient storage capacity, additional analytics does not replace warehouse modernisation. If the infrastructure is in order but decisions are delayed, the quality of data collection and processing becomes important. This approach helps to avoid financing a digital component without verifying its place in the production process.

Consensus on decisions is also necessary when organising processing. Electronic traceability links information about a batch of raw materials with storage and production operations, but it does not ensure physical preservation without monitoring temperature, humidity, and equipment. An information system can help identify areas of loss and distribute responsibility. Next, it requires technological actions, quality measurement, and calculation of the economic result. Therefore, it is advisable to develop an innovative project to change a

specific process, including equipment, data, competencies, and maintenance. This allows comparison of alternatives and identification of the combination that ensures acceptable costs and sustainability under the farm's conditions.

The Concept for the Development of the Agro-Industrial Complex for 2021–2030 sets the framework for sectoral modernisation; the study examines its current version as of the verification date (Government of the Republic of Kazakhstan, 2021). When analysing the results for 2023–2025, this framework does not replace information about the actual measures implemented. In the Ministry of Agriculture report (2026), integrating solutions into the “e-Agro-Industrial Complex” ecosystem is identified as a development direction. Consequently, the announced architecture must be distinguished from completed integration and proven economic effects.

The digitalization of public interaction and the digitalization of production have different immediate results. An electronic application can reduce administrative costs, and a monitoring system can improve information verification. A production effect arises only when business practices change. Therefore, the support project should be assessed at two levels: the quality and accessibility of the service, and the results of using the resource. This approach prevents conflating faster application processing with increased crop yields or reduced water consumption.

Cooperation can reduce barriers to accessing innovations through shared use of equipment, specialists, and information services. To achieve this, it is necessary to define the payment procedure, priority of access during the season, responsibility for maintenance, and rules for handling participants' data. The cooperative model is especially useful when a farm does not need to own expensive equipment on an ongoing basis. However, shared use also creates organisational risks: service overload, schedule conflicts, and unequal distribution of benefits. These should be taken into account when choosing an implementation model, along with the expected savings.

Discussion. The results show that sustainable development is linked to aligning technological equipment with the ability to change production solutions. This position aligns with the interpretation of digital agriculture as an organisational transformation presented in international literature. Kazakhstan's investment and resource statistics show the expansion of modernisation opportunities but do not indicate how effectively they are used. Therefore, the next research task is to shift from total investment volume and technical coverage to comparable data on costs, resources, and farm outcomes.

Of particular importance is the distinction between the novelty of a solution and its economic utility. For an enterprise with insufficient tracking of purchases and inventory, the priority improvement may be reliable transaction recording and establishing accountability. A more complex analytical system becomes useful after accumulating high-quality data and defining the task. This does not mean abandoning advanced technologies; rather, it sets the sequence for their

implementation. The choice should depend on the limitations of a specific process: a lack of information, physical infrastructure, competencies, or funding.

Regional adaptation is necessary due to differences in production profiles. For areas with irrigated agriculture, water accounting, network condition, and irrigation management are important. In grain-producing regions, the key challenge becomes the spatial heterogeneity of the field, moisture levels, and the precision of operations. For livestock farming, animal health, feeding, and traceability are important; for processing, the quality of raw materials and losses are key. A unified information infrastructure can support various tasks, but a universal technological package that does not account for local conditions increases the risk of inefficient spending.

Innovation financing should be linked to the stages of implementation. At the initial stage, problem diagnosis and a pilot with measurable parameters are required. After testing the technology, assess total cost of ownership, cash flow, and service organisation. Scaling is justified if the effect persists with expansion and does not require a disproportionate increase in costs. Subsidising the purchase without checking subsequent operation can result in equipment that is partially used or left unattended. Therefore, the conditions for maintaining operability and access to the service infrastructure are essential.

Environmental performance requires consideration of technology interactions. Irrigation automation and energy efficiency should be evaluated together, and the accuracy of protective equipment should be evaluated together with the risk of erroneous treatment and possible changes in biological load. Higher yields may reduce the need to expand crops, but this effect depends on market demand and land use. Therefore, sustainability cannot be assessed by a single improved indicator. It is advisable to use a small set of consistent indicators, with disclosure of initial values and measurement limitations.

Information security and data rights also affect economic sustainability. The agreement should define access to information, the purpose of its use, the possibility of transfer to third parties and the procedure for recovery. The manufacturer needs clear conditions for changing suppliers and maintaining their own records. The system must support redundancy and alternative operating procedures when communication is unavailable. These organisational requirements relate to the continuity of production and the ability to benefit economically from data, not just the technical security of the platform.

Social accessibility of digitalization requires the involvement of consulting services, educational organizations, and producers' associations. Training on specific production tasks and post-implementation support are required. For small farms, service fees, leasing, and resource sharing are promising options, provided the terms are transparent and service quality is verifiable. Such an arrangement expands access without assuming that every producer must own a full set of equipment. At the same time, the decision to cooperate should consider the scale of the operation, seasonality, and the ability to align participants' interests.

To empirically test the proposed model, observations before and after the implementation are required, along with a comparable group without the technology. When selecting the group, the crop, region, farm scale, land quality, and initial qualifications are taken into account. The assessment should control for weather conditions, prices, and changes in production volume. If more affluent farms are chosen for implementation, a simple comparison of averages will overestimate the potential effect. The pilot study should define the main indicators and measurement rules in advance, and present results with an uncertainty range. This design will make it possible to test the mechanism that is analytically substantiated in this work.

At the level of state policy, the study's practical outcome is a proposal to assess modernisation across the entire chain, from resource availability to sustainable economic effect. Reporting on implementation may include equipment operability, actual use of the service, resource indicators, and maintenance costs. International approaches help formulate criteria, but the national system must account for farm structures and regional constraints. The proposed model is not an assessment of the effectiveness of a specific program and requires adaptation when used for budgetary decisions.

An additional condition for scaling is related to separating technical operability from economic feasibility. The system can steadily transmit data and generate accurate forecasts, but it remains unprofitable with high maintenance costs or low production volume. Therefore, an independent economic assessment is required after the technical test. It includes initial investments, regular pay, employee time, maintenance, possible downtime, and the cost of abandoning the previous process. When comparing, several seasons are considered, since a single favourable year does not reflect the sustainability of the result. This verification sequence allows you to justify scaling and identify situations where a more affordable solution provides similar benefits to the manufacturer.

Conclusion. The sustainable development of the agro-industrial complex based on innovation and digital technologies requires coordination of production, financing, competencies, and data management. Technology becomes a factor of sustainability when information is used for a specific action, and its result is measured against economic, environmental, and social criteria. Expanding digital infrastructure without corresponding infrastructure and organisational support does not guarantee improved economic results.

An analysis of Kazakhstan's official data revealed a 56.3% increase in investment in the primary sector at current prices over 2024–2025, with a 51.8% growth in physical volume. Own funds remain the largest source of financing. The area of application of water-saving systems increased by 129.2% in 2023–2025. These changes characterise the conditions and technical scope of modernisation; they do not establish the share of digital costs or the causal effect of technology.

The proposed analytical model links observation, data verification, decision-making, execution, and outcome evaluation. The indicator system covers total cost,

resource intensity, development availability, and organisational reliability. The priorities are regional adaptation of solutions, service support, data compatibility and access of small farms to equipment and competencies. Further research should rely on corporate and business microdata, comparable pilots, and validation of results across multiple production seasons. This will allow us to move from analysing prerequisites to an evidence-based assessment of the contribution of innovation and digitalisation to the sustainable development of Kazakhstan's agro-industrial complex.

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