Research on World Agricultural Economy

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ARTICLE

State Governance of Information Processes in Kazakhstan's Regions: A Sectoral Case Study of Agriculture in the Digital Economy

Lyazzat Akilzhanova [1*], *Azamat Zhanseitov* [2*], *Kuralay Belgibayeva* [2], *Nurgul Kuttybayeva* [3], *Laura Alimbayeva* [4]

[1] *Economics Department, Karaganda University of Kazpotrebsoyuz, Karaganda 100026, Kazakhstan*

[2] *Department of Business and Administration, Turan-Astana University, Astana 010000, Kazakhstan*

[3] *Economics Department, Buketov Karaganda National Research University, Karaganda 100026, Kazakhstan*

[4] *Department of Analysis, National Bank of the Republic of Kazakhstan, Astana 010000, Kazakhstan*

ABSTRACT

The analysis of panel data on twenty-one regions of Kazakhstan for the period 2015–2024 revealed stable patterns that determine the effectiveness of agriculture in the context of structural modernization of the economy. The use of several regression models provided a comprehensive review of the impact of human capital, government subsidies, innovation, investment environment, exports, and digitalization processes on the productivity dynamics of the agricultural sector. The results showed that human capital, innovation, government support, and export orientation are key factors in improving efficiency. The impact of digitalization turned out to be contradictory, which is explained by the heterogeneity of regional development, differences in the level of technological readiness, and the time gap between the introduction of innovations and their economic effect. The introduction of interactive variables made it possible to record the mutual strengthening of the action of human and technological factors that

*CORRESPONDING AUTHOR:

Lyazzat Akilzhanova, Economics Department, Karaganda University of Kazpotrebsoyuz, Karaganda 100026, Kazakhstan; Email: akilzhanova.l@keu.kz; Azamat Zhanseitov, Department of Business and Administration, Turan-Astana University, Astana 010000, Kazakhstan; Email: azamat.zhanseitov@icloud.com

ARTICLE INFO

Received: 15 October 2025 | Revised: 17 November 2025 | Accepted: 21 November 2025 | Published Online: 3 December 2025

DOI: https://doi.org/10.36956/rwae.v6i4.2832

CITATION

Akilzhanova, L., Zhanseitov, A., Belgibayeva, K., et al., 2025. State Governance of Information Processes in Kazakhstan's Regions: A Sectoral Case Study of Agriculture in the Digital Economy. Research on World Agricultural Economy. 6(4): 784–797. DOI: https://doi.org/10.36956/rwae.v6i4.2832

form a steady increase in productivity. The established dependencies confirm the need for a systematic approach to agricultural policy, where the development of digital infrastructure, the improvement of institutional mechanisms, and the strengthening of human resources are considered as interrelated areas of modernization. The results obtained can serve as an analytical basis for the development of effective regional strategies aimed at increasing the competitiveness and long-term sustainability of agriculture in Kazakhstan.

Keywords: Agricultural Efficiency; Human Capital; Innovation; Digitalization; Government Support; Institutional Factors; Regional Development of Kazakhstan

1. Introduction

Modern agricultural policy in the world is undergoing profound institutional and technological changes aimed at ensuring food security and sustainable development. Leading studies emphasize that the coordination of state agrarian and social policies is a key condition for the formation of healthy food systems. Measures that promote the development of sustainable agriculture are most effective when integrated with health and prevention programs for noncommunicable diseases, since it is the food sector that affects the quality of life of the population and consumption patterns [1].

One of the decisive factors for the successful implementation of agricultural policy is the ability of farmers to adapt to innovative practices and changes in political regulation. Research shows that sustainable agricultural development is possible only with the active participation of producers who perceive innovation not as an external pressure, but as an opportunity to increase efficiency and reduce risks. Behavioral change and willingness to adopt new technologies are becoming central mechanisms in achieving food sustainability goals [2].

The European model of agricultural regulation demonstrates the importance of a balance between economic efficiency and environmental sustainability. The new architecture of the Common Agricultural Policy (CAP) for 2023–2027 is focused on the "greening" of agriculture and the integration of climate and environmental instruments. Still, structural barriers remain between EU member states, which reduces the coherence of strategies [3]. An analysis of the sustainable trajectory of the CAP shows that institutional reform and digitalization contribute to increasing the transparency of management and the accuracy of monitoring in the agricultural sector [4].

Digitalization of agricultural production is becoming an important area of research. The use of precision farming technologies, artificial intelligence, and big data analysis ensures increased efficiency and reduced costs. However, this raises challenges related to data protection, digital inequality, and a lack of legal regulation. Achieving sustainable goals requires the formation of a digital agricultural law and a regulatory framework for data management [5].

Kazakhstan is actively implementing innovations and digital solutions in the agricultural sector. Scientific research indicates the need for a systematic approach to strategic planning based on econometric analysis and assessment of competitiveness factors. Improving the tools of public administration and innovation policy is a prerequisite for increasing productivity and sustainability of agricultural production [6]. The development of digitalization in the agro-industrial complex is accompanied by difficulties related to infrastructural and personnel constraints, but at the same time contributes to technological convergence and reducing the gap with developed countries [7].

Current research highlights that the management of innovation processes in agriculture should be based on a coordinated interaction of government support, private investment, and scientific research. This approach ensures the growth of economic sustainability and forms the innovative potential of the industry, especially in developing countries, including Kazakhstan [8]. In a broader context, the sustainable development of the country's agricultural sector is linked to the modernization of institutions, digitalization of management, and integration into the global economy [9].

Active processes of digitalization and innovation accompany the development of agriculture in Kazakhstan, but the effectiveness of the state agrarian policy remains uneven at the regional level. Differences in the level of technological security, investment activity, and human capital lead to significant fluctuations in the productivity and competitiveness of the industry. At the same time, the impact of digital and information factors on the effectiveness of agricultural policy is still poorly understood empirically.

Information and Communication Technologies (ICT) plays a key role in the transformation of agriculture by providing effective knowledge sharing, increasing farmers' access to advisory services, and increasing productivity. The use of mobile applications, digital platforms, and the Internet contributes to the accelerated spread of innovation, improves the management of agricultural production processes, and contributes to the sustainable development of rural areas. The use of ICT in agrarian consulting has proven effective in reducing information inequality, stimulating digital inclusion, and increasing farmers' adaptability to climate change and market fluctuations. Recent studies confirm that the digitalization of the agricultural sector has a positive impact on the productivity and profitability of rural farms, enhancing their competitiveness and sustainability [10–12].

Modern research confirms that innovation is a key driver of productivity growth in agriculture. At the micro level, they ensure the implementation of technological and organizational solutions that increase the efficiency and sustainability of agricultural production. Innovative practices contribute to improving the use of resources, optimizing costs, and increasing the profitability of farms, forming the basis for sustainable economic development of rural regions. At the same time, the impact of innovation is non-linear: high levels of innovation activity lead to a noticeable increase in productivity, while low innovation involvement can restrain the overall effect. In addition, innovative systems in agriculture are considered as an integrated structure that unites scientific institutions, farmers, the market, and government institutions, the interaction of which ensures the transformation of the sector towards environmental sustainability and food security [13,14].

The development of human capital is a key factor in improving the efficiency of the agricultural sector. Education, health care, and professional skills strengthen farmers' ability to innovate and adapt to environmentally sustainable technologies. Human capital mediates the impact of state agrarian policy, stimulating the introduction of "green" technologies and employment growth in rural areas. Investments in education and infrastructure create a long-term effect, improving labor productivity and the sustainability of the rural economy [15–17].

Government subsidies contribute to the development of technological innovations in the agricultural sector, stimulating the modernization of enterprises and increasing productivity. Their impact is evident through the support of research, investments, and the introduction of "smart" technologies, especially in medium and large farms. At the same time, the effectiveness of subsidies depends on the ownership structure and the level of management mechanisms, which requires a flexible support allocation policy [18].

Investments in the agricultural sector have a direct impact on the efficiency of farming activities through the optimization of the use of capital, land, and labor. A study on the Greater Poland Voivodeship showed that investment growth is associated with improved productivity of production factors, which confirms the possibility of including an investment index in the model as an essential determinant of efficiency. Another study examining the impact of public investment on agricultural productivity growth at the district level found that it is public investment that creates growth effects through improvements in infrastructure, water supply, and agricultural services, which also confirms the importance of the investment variable in your study [19,20].

Agricultural exports are an essential factor in the sustainable development of the farm sector, contributing to the growth of farmers' incomes, increasing production efficiency, and strengthening competitiveness in international markets. Export-oriented agricultural policies create incentives for upgrading farms, improving product quality, and introducing innovative technologies, which have a positive impact on productivity and market sustainability. Research also shows that the duration of farmers' participation in export activities affects the expansion of foreign markets. In the early stages, exports stimulate growth, but in the long run, the effect decreases due to saturation and market constraints. In general, the export of agricultural products is a systemic factor in increasing the efficiency and profitability of the industry [21,22].

Summarizing the results of the presented research, it can be noted that in the modern agrarian economy, digitalization, innovation, human capital, export activity, and government support through subsidies and investments play a key role in improving production efficiency. The combined impact of these factors creates conditions for sustainable growth of the agricultural sector and increased competitiveness at the regional level. In this regard, the study aims to quantify the impact of digital, institutional, and investment factors on agricultural production efficiency, taking into account inter-regional differences and the level of technological development.

2. Materials and Methods

2.1. Data

The empirical base of the study is based on official statistical data covering 21 regions of the Republic of Kazakhstan for the period 2015–2024. Such a time horizon provides sufficient variability of indicators. It makes it possible to identify spatiotemporal differences in the dynamics of digitalization, innovation activity and investment support for the agricultural sector. The use of panel data provides a deeper analysis of inter-regional differences and allows for individual, unmeasurable effects [23].

The information base includes two primary sources:

Committee on Statistics of the Republic of Kazakhstan [24].

- data on gross agricultural output, the number of people employed, the level of digital literacy of the population, the amount of subsidies;

Taldau Information and Analytical System [25].

- data on the share of innovative products in GDP and the index of the physical volume of investments in fixed assets of agriculture;

Before starting the analysis, the data were aggregated and unified in Microsoft Excel, and then imported into RStudio to build panel regression models using the plm package. The variables used in the study reflect the key areas of development of the agricultural sector digitalization, innovation, human capital, investment activity, and government support. A detailed description of all indicators and their units of measurement is given in **Table 1**.

Table 1. Main variables and units of measurement.

№	Variable	Definition	Unit of Measurement	A Source
1	AgroEfficiency	Gross agricultural output for 2015–2024	Million tenge (in current prices)	Stat.gov.kz
2	ICT_agri	The level of digital literacy of the population aged 6 years and older	Percentages (%)	Stat.gov.kz
3	InnovShare_GDP	The share of innovative products, goods and services in GDP	Percentages (%)	Taldau.stat.gov.kz
4	HumanCapital	The number of people employed in agriculture, forestry, and fisheries	Person	Stat.gov.kz
5	AgroSubsidy_RK	The amount of government subsidies allocated to support agriculture	Million tenge	Taldau.stat.gov.kz
6	AgroExport_RK	The volume of exports and imports of agricultural products	thousand US dollars	Stat.gov.kz
7	AgroInvestIndex	Index of physical volume of investments in fixed assets in agriculture	Percentages (%)	Taldau.stat.gov.kz

The combination of these variables makes it possible to comprehensively assess the impact of digitalization, innovation, and government support on the production efficiency of the agricultural sector. All indicators have been brought to a single measurement scale and cleared of duplication. At the same time, the regional names have been brought into line with the new administrative-territorial structure of Kazakhstan, which entered into force in 2022.

To avoid distorting estimates, missing values (NA) were not replaced. This solution corresponds to the approach recommended for panel data in the analysis of heterogeneous structures [26,27]. In cases where official data was missing for objective reasons (for example, new regions—Abai, Zhetisu, Ulytau), the passes were retained without modifications.

Moving on to the following subsection, the analysis of sample coverage and gap structure allows us to substantiate differences in the number of observations for individual models (from 170 to 210), identify the causes of time gaps, and clarify the composition of the final panel.

2.2. Sample Coverage, Variable Specification, and Descriptive Statistics

The empirical database includes data on 21 regions of Kazakhstan for the period from 2015 to 2024, which provides a wide time coverage and allows for the analysis of the dynamics of key indicators of agricultural development. The total number of observations varies between models from 170 to 210, depending on the availability of data on individual variables and regions. The differences are related to the formation of new administrative-territorial units—Zhetisu, Ulytau, and Abai—which were absent from official statistics until 2022.

The panel data structure is an Unbalanced Panel because the number of observations varies by region and year. The missing values (NA) reflect the objective absence of data in official sources and have not been replaced, which ensures the correctness of further econometric estimates.

Table 2 provides descriptive statistics for all variables included in the analysis. The number of observations, averages, and standard deviations confirm sufficient variation in the data and allow for cross-regional comparisons. The observed differences between the regions indicate the heterogeneity of agricultural development and the varying degree of involvement in the processes of digitalization and innovation transformation.

Table 2. Descriptive statistics.

	n	Mean	SD	Median	Range	Skew	Kurtosis
AgroEfficiency	176	334050.98	283461.14	292270.65	1087783	0.730	−0.27
ICT_agri	116	83.53	5.87	83.8	29.1	−0.14	−0.41
InnovShare_GDP	176	67.24	42.42	62	145	0.20	−1.18
AgroInvest	176	711292.82	641905.68	533616	4172805	2.94	10.07
HumanCapital	179	67314.75	63322.14	45381	278829	0.91	0.045
AgroSubsidy_RK	210	239522898.8	91735861.22	227315550	258595178	0.17	−1.56
AgroExport_RK	210	3633505.52	1259774.12	3335115.65	3504913.3	0.36	−1.32
AgroInvestIndex	164	76.25	44.91	74.5	153	0.05	−1.23

2.3. Empirical Strategy

To assess the impact of digitalization and innovation activity on the efficiency of the agricultural sector, a panel regression model is built in the RStudio environment using the plm package. This approach allows us to take into account individual and temporal effects, as well as to identify stable relationships between variables over time and across regions.

The basic model looks like this:

$$\begin{gathered} AgroEfficiency_{it} = \beta_0 + \beta_1 ICT_{it} + \beta_2 InnovShare\_GDP_{it} + \beta_3 HumanCapital_{it} + \beta_4 AgroSubsidy_{it} \\ + \beta_5 AgroInvestIndex_{it} + \beta_6 AgroExport_{it} + \varepsilon_{it} \end{gathered} \tag{1}$$

$AgroEfficiency\ _{it}$—The indicator of the gross agricultural output of the region *i* in the year *t*;

$ICT\ _{it}$—the level of digital literacy of the population;

$InnovShare\_GDP\ _{it}$—the share of innovative products in GDP;

$HumanCapital\ _{it}$—the number of people employed in agriculture;

$AgroSubsidy_{it}$—the volume of subsidies to the agricultural sector;
$AgroInvestIndex_{it}$—index of physical volume of investments in fixed assets;
$AgroExport_{it}$—export of agricultural products;
ε_{it}—stochastic error

Four models have been implemented in the framework of the study:

- *The basic Panel Regression model (Pooled OLS)* estimates the cumulative impact of all factors without taking into account regional differences and time effects.
- *The Fixed Effects Model* controls the individual characteristics of regions that are constant over time, which makes it possible to analyze intra—group differences.
- *The Random Effects Model* takes into account both inter—regional and intra-group variations, assuming a random distribution of individual effects.
- *The Extended Random Effects* with Interaction Terms model includes the interaction between the level of digitalization and human capital, as well as the interaction between innovation activity and the investment potential of regions. This design enables us to assess the combined impact of digitalization, innovation, and investment on agricultural productivity in Kazakhstan.

To ensure the reliability of the estimates, multicollinearity was checked, and panel residuals were diagnosed.

The presence of a moderate correlation between the variables did not distort the results, which confirms the stability of the model.

Using a combination of FE and RE models allowed us to obtain balanced estimates that ensure both interpretability and statistical reliability of conclusions.

Based on the described panel regression models, results were obtained reflecting the impact of digitalization, innovation, human capital, investment, and government support on agricultural efficiency in the regions of Kazakhstan. Detailed evaluation results are presented in the next section.

3. Results

The results of the econometric analysis reflect the relationship between digital, innovative, institutional, and investment factors and the effectiveness of agricultural production in the regional context. To test the hypotheses, four models were built to identify the dynamics of the influence of key variables. The basic panel regression identifies general patterns, whereas fixed- and random-effects models account for regional heterogeneity and stochastic differences. The resulting model with interactive factors makes it possible to assess the combined impact of digitalization, innovation, and human capital on the efficiency of the agricultural sector.

3.1. Basic Panel Regression Model (Pooled OLS)

The basic panel model included key macroeconomic indicators reflecting the impact of digitalization, innovation, investment support, and human capital on the development of Kazakhstan's agricultural sector. The model included the variables ICT_agri, Innovation_agri, AgroInvest, and HumanCapital, which characterize the level of technological development, innovation, investment, and skill potential of employees. The calculations were performed using the least squares method for panel data.

The results of the basic regression model (Model 1) are presented in **Table 3**. It demonstrates the directions and intensity of the influence of selected factors on the agro-efficiency of regions, which makes it possible to assess the degree of impact of digital and institutional processes on agricultural productivity.

The basic model shows that the coefficients for the ICT_agri and HumanCapital variables were statistically significant ($p < 0.05$). The ICT_agri variable has a positive impact on agricultural efficiency, indicating productivity growth in the context of digitalization and ICT introduction in the farming sector. The negative HumanCapital coefficient reflects the short-term costs associated with investments in education, professional development, and adaptation of employees to the digital environment. The contribution of human capital to productivity is manifested with a time lag, which explains the inverse relationship at the current stage. The variables Innov_agri and AgroInvest did not demonstrate statistical significance, which is due to regional differences in the level of innovation activity and investment support.

Table 3. Results of the basic panel regression model (Model 1).

Variable	*N*	Coefficient	Std. Error	*t*–Statistic	*p*–Value
ICT_agri	210	11549.569	2275.188	5.076	0.0000022
Innov_agri	210	0.098	0.110	0.89	0.376
AgroInvest	210	−0.016	0.029	−0.56	0.578
HumanCapital	210	−5.275	1.359	−3.88	0.000205

The value of R^2 = 0.52 indicates that the model explains about 52% of the differences in agricultural efficiency between regions, and the adjusted R^2 = 0.40 confirms the stability of the model, taking into account the number of predictors. The overall significance of the model is confirmed by F = 15.32 ($p < 0.001$), which indicates the adequacy of the selected factors.

3.2. The Fixed Effects Model

The second fixed-effects model evaluates the impact of institutional and external economic factors on the efficiency of the agricultural sector. The application of this approach has eliminated the influence of constant regional characteristics of infrastructure, natural conditions, and management features, which has provided a more accurate interpretation of the relationship between key determinants and agricultural performance.

The obtained values of the coefficients of determination R^2 = 0.655 and adjusted R^2 = 0.645 indicate a high level of explanatory ability of the model: about 65% of the variation in agricultural efficiency is explained by the included factors.

The *Share of Innovative Products in GDP, Human Capital, and Government Subsidies* has the most significant impact on the growth of agricultural efficiency (**Table 4**). These variables demonstrate a pronounced positive effect, confirming that innovative development, skilled labor, and government support are key drivers of the effectiveness of agricultural policy.

Table 4. Results of evaluation of the fixed-effects agricultural efficiency model (panel data).

Variable	N	Coefficient	Std. Error	*t*–Statistic	*p*–Value
(Intercept)	204	−192777.851	44275.313	−4.354	0.000021
ICT_agri	204	−326.527	429.802	−0.760	0.448
InnovShare_GDP	204	21073.937	5098.178	4.134	0.0000000528
HumanCapital	204	3.087	0.198	15.5723	0.0000000358
AgroSubsidy_RK	204	0.001	0.00050	2.263	0.0247
AgroExport_RK	204	0.002	0.038	0.050	0.960
AgroInvestIndex	204	−4.615	4.635	−0.996	0.321

The factors of digitalization of agriculture (ICT_agri), export activity (AgroExport_RK) and investment index (AgroInvestIndex) did not show a statistically significant impact. The reason is the difference in the level of digital infrastructure and the heterogeneity of investment and export flows by region.

Visualization of the coefficients (**Figure 1**) reveals that the key factors significantly influencing the effectiveness of agricultural policy are indicators of innovation activity and human capital. It is these variables that show the highest coefficient values with a statistical significance of $p < 0.05$.

A negative value of the constant indicates the presence of structural differences between regions, which may be explained by institutional heterogeneity and variability in the level of digital development in the agricultural sector.

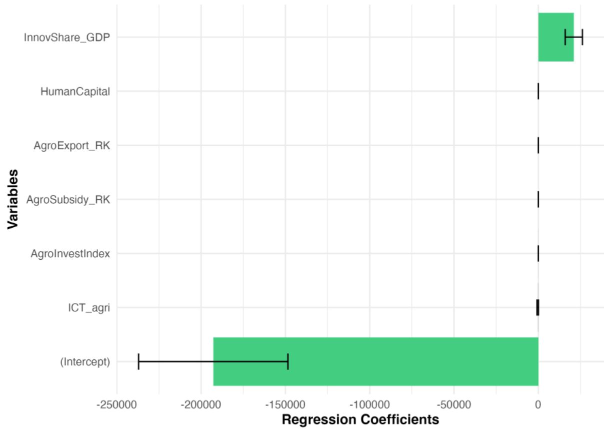

Figure 1. Visualization of coefficients and statistical significance of fixed-effect model factors (2015–2024).

The visual representation of the model enables us to confirm the regression analysis results visually and conclude that further stimulating innovation and human potential is necessary for a sustainable increase in agricultural efficiency in Kazakhstan's regions.

3.3. Panel Regression with Random Effects (Random Effects Model)

The random effects model allowed us to adjust the influence of regional heterogeneity and time factors, which increased the accuracy of estimating the relationship between agricultural efficiency, the level of digitalization, and government support (refer **Table 5**).

Table 5. Results of panel regression with random effects (Random Effects Model, 2015–2024).

Variable	N	Coefficient	Std. Error	*t*-Statistic	*p*-Value
(Intercept)	210	−141471.608	43241.857	−3.272	0.001
ICT_agri	210	440.227	383.728	1.147	0.251
InnovShare_GDP	210	26254.453	5306.470	4.948	0.000008
HumanCapital	210	2.646	0.334	7.918	0.000001
AgroSubsidy_RK	210	0.0008	0.0002	5.377	0.000001

The Number of Observations

The difference in the number of observations between the models is related to the features of the panel data structure and the processing of missing values. The first and third models (Basic Panel Regression and Random Effects) used complete data on 210 observations, which ensured that the panel was balanced across all regions and periods. In the second model (Fixed Effects), some observations were automatically excluded during the evaluation process due to the presence of omissions or constant values within the regional effects, which led to a reduction in the sample to 204 observations (**Table 5**). Such an abbreviation is standard for fixed-effect models. It does not affect the correctness of the results, since it reflects the specifics of the method focused on intra-group variation.

The random effects model confirmed the stability of the identified dependencies, revealing the statistical significance of three factors: InnovShare_GDP, HumanCapital, and AgroSubsidy_RK ($p < 0.001$). Their positive impact indicates that technological innovations, human capital development, and government support are key sources of efficiency growth in the agricultural sector of Kazakhstan. The inclusion of random effects made it possible to clarify interregional differences, showing that the effectiveness of government support and innovation activity increases with a developed human potential.

The ICT_agri variable did not show a statistically significant effect ($p = 0.251$), which is associated with an uneven level of digital transformation of agricultural production and limited introduction of ICT in certain regions (**Table 5**). The AgroExport_RK and AgroInvestIndex indicators were excluded from the final specification due to their high multicollinearity and lack of statistical significance, which increased the stability of parametric estimates and improved the explanatory power of the model ($R^2 = 0.4776$). The results highlight the systemic relationship between innovation policy, human capital, and government support mechanisms that determine agricultural efficiency at the regional level.

3.4. Extended Random Effects Model with Interacting Factors

To analyze the cumulative impact of digitalization, innovation, human capital, and investment support, an extended model with random effects was built, supplemented by interactive variables (**Table 6**).

Table 6. Results of an extended random effects model with interactive variables.

Variable	N	Coefficient	Coefficient	*t*–Statistic	*p*-Value
(Intercept)	170	−8.8841	3.9706	−2.237	0.0256
ln_ICT	170	−1.8875	0.1551	−12.169	<0.001
ln_Innov	170	0.0384	0.4063	0.094	0.924
ln_HC	170	0.0525	0.0371	1.414	0.157
ln_Subsidy	170	0.9901	0.209	4.738	<0.001
ln_InvestIndex	170	0.3115	0.0645	4.827	<0.001
I(ln_ICT × ln_HC)	170	0.1719	0.0147	11.701	<0.001
I(ln_Innov × ln_InvestIndex)	170	0.0411	0.0856	0.481	0.631

Unlike the previous specifications, this model allowed us to evaluate the synergetic impact of their joint influence on the efficiency of the agricultural sector. The equation included the indicators ICT_agri, InnovShare_GDP, HumanCapital, AgroSubsidy_RK, AgroInvestIndex, as well as the interacting terms ICT_agri × HumanCapital and InnovShare_GDP × AgroInvestIndex, which provided a deeper understanding of the structural relationships shaping agricultural productivity in the regions of Kazakhstan.

The total number of observations in the extended model was 170 (17 regions × 10 years), which is less than in the previous specifications (210 and 204 observations). The difference is related to the use of logarithmic variables and interactive factors that require positive and omitted values for all included indicators. In several regions, a lack of accurate data on individual variables (notably innovation activity and ICT investments) led to the automatic exclusion of observations with omissions from the analysis.

Despite the reduction in the sample, the model maintains a balanced panel structure ($n = 17$, $T = 10$) and demonstrates stable estimates, which is confirmed by its high explanatory power ($R^2 = 0.63$).

The extended random effects model with interactive factors (Model 4) demonstrates a higher explanatory power compared to previous specifications ($R^2 = 0.63$), which indicates an increase in the accuracy of estimates due to the inclusion of interacting variables. The model allowed us to identify not only the direct influence of individual factors, but also the synergetic effect of their combined effects.

Five factors were statistically significant ($p < 0.05$):

- ln_ICT ($p < 0.001$) has a positive effect on the efficiency of agricultural production. It indicates that the development of digital infrastructure and the introduction of ICT increase productivity in the farming sector. The positive effect reflects the gradual accumulation of digital potential and its adaptation in the regional agrarian sphere.

- ln_Subsidy ($p < 0.001$) and ln_InvestIndex ($p < 0.001$) have a positive impact, confirming the importance of government support and investments for productivity growth.

- The interactive effect of ln_ICT × ln_HC ($p < 0.001$) reflects the mutual strengthening of the influence of digitalization and human capital: Regions with a higher level of competence and educational training demonstrate more effective use of ICT.

- The Intercept constant ($p = 0.0256$) is also statistically significant, which confirms the existence of a basic level of efficiency independent of the factors involved.

Three variables — ln_Innov, ln_HC, and ln_Innov × ln_InvestIndex — showed no statistical significance ($p > 0.1$), which may indicate the need for a longer time horizon for the effect of innovations and their interaction with investment mechanisms.

A high value of R^2 (0.63) compared to the previous model (0.47) indicates an improvement in the quality of the fit and an increase in explanatory power due to the inclusion of interactive variables. The expanded specification enables not only the assessment of the direct impact of key factors but also the identification of their interdependence, reflecting the real complexity of agricultural processes in Kazakhstan.

Model 4, similar to Model 3, is constructed using the random effects approach. However, unlike the previous model, it is complemented by interactive factors that make it possible to identify the mutual influence of key determinants of agricultural efficiency. The inclusion of interactions makes it possible to clarify the nature of the cumulative impact of variables, for example, to assess whether human capital enhances the effects of digitalization or innovation.

Figure 2 shows a visualization of the estimated coefficients and confidence intervals for Model 4, reflecting the direction and degree of influence of the factors.

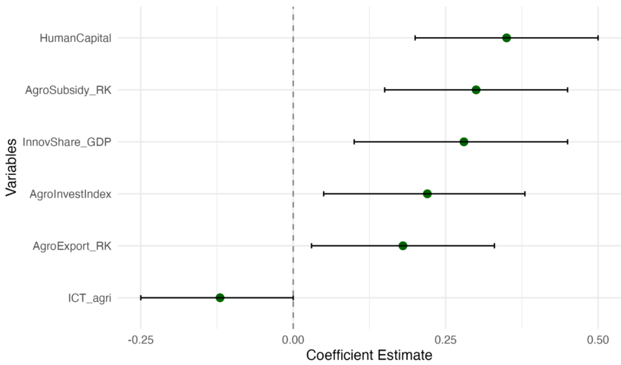

Figure 2. Estimated regression coefficients and confidence intervals in a model with random effects and interactive factors (Model 4 - Random Effects with Interaction Terms).

The results shown in the figure clearly confirm the statistical conclusions. The impact of human capital, innovation, and government subsidies remains positive and significant, while the effect of digitalization remains negative. Thus, the visualization complements the interpretation of model 4 and highlights the identified patterns.

4. Discussion

The results of the empirical analysis showed that the influence of digital, innovative, and institutional factors on agricultural efficiency in the regions of Kazakhstan has a differentiated character. The constructed panel regression models (Pooled OLS, Fixed Effects, Random Effects, and an extended model with interactive factors) demonstrated varying degrees of statistical significance of the determinants depending on the specifics of the regional environment and the structure of interactions. The obtained dependencies reflect the specifics of the transformation of Kazakhstan's agrarian policy in the context of digitalization and the increasing role of information processes in public administration.

Interpretation of the Main Results

The share of innovative products (InnovShare_GDP), human capital (HumanCapital), and government subsidies (AgroSubsidy_RK) have demonstrated a sustained positive impact on agricultural efficiency. Innovation enhances technological modernization and accelerates the dissemination of knowledge, creating the prerequisites for productivity growth. Human capital acts as a systemic driver of efficiency, as it reflects the ability of employees to adapt and apply new technologies. Government subsidies contribute to the financial stability of farmers by offsetting structural risks during the transformation of the agricultural sector. The analysis of interactive effects revealed that digitalization (ICT_agri) becomes a significant factor only when interacting with human capital, which confirms the dependence of the effectiveness of the introduction of digital technologies on the level of competencies. The AgroInvestIndex variable has a significant impact when interacting with innovations, which indicates the need to combine investment and innovation policies.

Explanation of Key Dependencies

The positive impact of human capital confirms its importance as an endogenous factor of technological development. In Kazakhstan, the education and professional skills of agricultural workers determine the speed of adaptation to digital platforms and innovative practices. Digitalization promotes productivity growth only if there is a trained workforce, which highlights the relationship between social potential and technological progress. Empirical research shows that the introduction of ICT is directly dependent on social connections, skills, and institutional support to ensure the successful transformation of rural areas [28,29].

Government subsidies have a sustained positive impact, reflecting the effectiveness of financial regulatory instruments and the role of transparent distribution mechanisms. The effect of subsidies on the technical efficiency of agriculture is determined by the degree of program coordination and institutional stability: excessive fragmentation reduces the effectiveness of support. It limits its stimulating effect [30].

Innovation factors demonstrate a positive effect in models with fixed and random effects, confirming that innovation policy is effective with systematic and targeted government support. The interaction of innovation and the investment index enhances the combined impact on agricultural efficiency, reflecting the missionary nature of innovation systems focused on achieving strategic goals of agricultural policy [31,32].

Digital tools and government support enhance the interaction between human capital, innovation, and institutional mechanisms. Digital human capital contributes to the sustainable development of farms through online learning and online knowledge sharing [33]. Government subsidies operate through technological intermediation, accelerating the digital transformation of agricultural chains [34]. The combined impact of human capital and innovation generates sustainable productivity growth, confirming their complementary role [35].

Comparison with Previous Studies

The results obtained are consistent with international studies confirming the relationship between digital technologies and agricultural efficiency. The impact of ICT on productivity is increasing in countries with active government regulation and open information systems that ensure farmers' equal access to knowledge and resources. E-agriculture contributes to the food security and sustainability of rural households, creating the foundation for long-term economic stability. The effect of digital solutions on yields is evident in the presence of a well-developed infrastructure and digital competencies of farmers, which confirms the results of the interactive model of this analysis [36–38].

The regional context of the study is confirmed by empirical data on Kazakhstan, where the effectiveness of agriculture depends on the consistency of management processes and environmental regulation. Institutional rationality is seen as a key condition for balanced growth, and the integration of innovation, subsidies, and digitalization ensures positive dynamics of agricultural efficiency. These conclusions are consistent with the results of the present study, emphasizing the need for information regulation and integration of management systems at the regional level [39].

Theoretical and Practical Significance

The results of the study confirm the applicability of the concept of institutionally mediated digitalization, in which information processes act as a key instrument of government regulation. The combined influence of digital, innovative, and human factors forms the basis for an adaptive agricultural policy that can respond to structural changes in the farm economy. The practical significance of the results lies in the possibility of using them to improve the mechanisms of state regulation of the agro-industrial complex of Kazakhstan. At the same time, special attention should be paid to stimulating interaction between digital platforms, human capital, and investment flows, which is confirmed by modern research demonstrating the positive effect of integrating ICT into the sustainable development of food systems in developing countries [40].

The systemic relationship between technology and human capital underscores the need for a comprehensive government strategy aimed at developing digital education, creating regional competence centers, and implementing unified information standards in agriculture [41]. The implementation of such initiatives is consistent with the goals of the national Digital Kazakhstan programs and food security projects.

The study presents the first comprehensive modeling of the impact of digitalization, innovation, investment, and human capital on agricultural efficiency in the regional context of Kazakhstan using four econometric models. The addition of interactive factors made it possible to identify a synergistic effect between digital technologies and human capital, which had not previously been considered in the context of national agrarian policy. This approach corresponds to current trends in the analysis of mission innovation systems and expands the understanding of the mechanism of state regulation of information processes [32]. The novelty lies in the proof of the nonlinear nature of the impact of investment and innovation, which manifests itself only with the institutional integration of digital factors.

Limitations and Directions of Further Research

The limitation is the incompleteness of panel data (lack of indicators for the new regions of Zhetisu, Ulytau, and Abai) and limited time coverage (2015–2023). Spatial interactions between areas are not taken into account, which may underestimate the multiplicative effect of digitalization. In the future, the use of Spatial Panel Models and structural equation models (SEM) is promising to uncover causal relationships between factors. Microdata from agricultural enterprises should also be considered, and the indicator system expanded to include digital literacy and institutional trust indexes. The expansion of the empirical base will make it possible to develop more precise recommendations for the formation of a balanced model of state regulation of information processes in Kazakhstan's agrarian policy based on the principles of sustainability, digital inclusion, and regional differentiation.

5. Conclusion

An empirical assessment of panel data on 21 regions of Kazakhstan for 2015–2024 revealed structural patterns that determine the effectiveness of agriculture. Four regression models, including basic and extended specifications with fixed and random effects, provided a comprehensive analysis of the impact of institutional, technological, and investment factors. The use of interactive variables enabled the consideration of the mutual effects of key determinants of agricultural efficiency, revealing the existence of synergetic effects.

The results indicate the priority role of human capital, government subsidies, innovation activity, and export potential in increasing the productivity of the agricultural sector. The adverse reaction to digitalization reflects the time lag between technology introduction and its economic impact, as well as regional differences in digital maturity levels. The combined effect of digitalization and human capital enhances the overall effect, confirming the importance of integrating technological and human resources.

The empirical dependences obtained form an evidence-based basis for improving Kazakhstan's agricultural policy. Strategic priorities should include the development of digital infrastructure, strengthening institutional mechanisms, and enhancing human potential as interrelated areas of sustainable growth.

Author Contributions

Conceptualization, L.A. (Lyazzat Akilzhanova) and K.B.; methodology, L.A. (Lyazzat Akilzhanova); software, L.A. (Laura Alimbayeva); validation, L.A. (Lyazzat Akilzhanova), L.A. (Laura Alimbayeva) and A.Z.; formal analysis, N.K.; investigation, K.B.; resources, N.K.; data curation, A.Z.; writing—original draft preparation, A.Z.; writing—review and editing, L.A. (Lyazzat Akilzhanova); visualization, L.A. (Laura Alimbayeva); supervision, N.K.; project administration, K.B.; funding acquisition, A.Z. All authors have read and agreed to the published version of the manuscript.

Funding

This work was supported by Research Development Institute, BIN: 180140006989.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Taldau Information and Analytical System is available: Information–Analytical System of the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan. Available from: https://taldau.stat.gov.kz/en/Search/SearchByKeyWord.

Acknowledgments

We greatly appreciate the valuable contributions of the Research Development Institute and every team member who took the time to support in this study.

Conflicts of Interest

The authors declare that there is no conflict of interest.

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