



Rural Infrastructure Transformation and Climate Adaptation in Kazakhstan

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ABSTRACT

Today, the impact of climate change on agriculture is increasing and there is a need to rethink the role of rural infrastructure as a key factor in the sustainability and adaptive potential of the agricultural sector. The aim of the study is to assess the impact of rural infrastructure development on the sustainability of agriculture in Kazakhstan, taking into account regional differentiation and climatic factors. The methodological basis of the research includes methods of descriptive statistics, comparative analysis and econometric modeling. Panel data from the Bureau of National Statistics of the Republic of Kazakhstan on five macro-regions of Kazakhstan for 2010-2025 were used. The results showed that there is a stable positive relationship between infrastructure development and agricultural sustainability. In the basic model, an increase in the infrastructure index by 1 unit leads to an increase in the sustainability index by 0.58 ($\beta = 0.58$; $R^2 = 0.81$). The extended model has a higher explanatory power and shows that the greatest impact is exerted by water infrastructure ($\beta = 0.34$), followed by digital ($\beta = 0.29$) and transport ($\beta = 0.17$) components. The regional analysis revealed a significant differentiation: the maximum values of sustainability are observed in the Northern macroregion, while the Western macroregion remains the most vulnerable. The results obtained confirm that rural infrastructure acts as a systemic mechanism for adaptation to climate change, but its effectiveness is determined by its structural balance and regional conditions. The greatest effect is achieved with the integrated development of water, digital and transport infrastructure.

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Ауыл инфрақұрылымының трансформациясы және климаттық өзгерістерге бейімделу

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ТҮЙІН

Бүгінгі таңда климаттық өзгерістердің ауыл шаруашылығына әсері күшейіп отыр, бұл аграрлық сектордың тұрақтылығы мен бейімделу әлеуетінің негізгі факторы ретінде ауылдық инфрақұрылымның рөлін қайта қарастыру қажеттілігін айқындайды. Зерттеудің мақсаты – өңірлік дифференциация мен климаттық факторларды ескере отырып, Қазақстандағы ауылдық инфрақұрылым дамуының ауыл шаруашылығының тұрақтылығына әсерін бағалау. Зерттеудің әдіснамалық негізі сипаттамалық статистика, салыстырмалы талдау және эконометрикалық модельдеу әдістерін қамтиды. Қазақстан Республикасының Ұлттық статистика бюросының 2010–2025 жж. кезеңіндегі бес макроөңір бойынша панельдік деректері пайдаланылды. Нәтижелер инфрақұрылым дамуы мен ауыл шаруашылығының тұрақтылығы арасында тұрақты оң өзара байланыс бар екенін көрсетті. Негізгі модельде инфрақұрылым индексінің 1 бірлікке артуы тұрақтылық индексінің 0,58-ге өсуіне алып келеді ($\beta = 0,58$; $R^2 = 0,81$). Кеңейтілген модель жоғары түсіндіру қабілетіне ие екенін көрсетіп, ең үлкен әсер су инфрақұрылымына тиесілі екенін айқындайды ($\beta = 0,34$), одан кейін цифрлық ($\beta = 0,29$) және көлік ($\beta = 0,17$) компоненттері келеді. Өңірлік талдау айтарлықтай дифференциацияны анықтады: тұрақтылықтың ең жоғары мәндері Солтүстік макроөңірде байқалса, Батыс макроөңір ең осал болып қала береді. Алынған нәтижелер ауылдық инфрақұрылымның климаттық өзгерістерге бейімделудің жүйелік механизмі ретінде әрекет ететінін растайды, алайда оның тиімділігі құрылымдық теңгерімділік пен өңірлік жағдайларға байланысты анықталады. Ең жоғары тиімділік су, цифрлық және көлік инфрақұрылымдарын кешенді дамыту кезінде қол жеткізіледі.

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Трансформация сельской инфраструктуры и адаптация к климатическим изменениям

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АННОТАЦИЯ

Сегодня влияние климатических изменений на сельское хозяйство усиливается, что обуславливает необходимость переосмысления роли сельской инфраструктуры как ключевого фактора устойчивости и адаптационного потенциала аграрного сектора. Целью исследования является оценка влияния развития сельской инфраструктуры на устойчивость сельского хозяйства Казахстана с учетом региональной дифференциации и климатических факторов. Методологическая основа исследования включает методы описательной статистики, сравнительного анализа и эконометрического моделирования. Использованы панельные данные Бюро национальной статистики РК по пяти макрорегионам Казахстана за 2010–2025 гг. Результаты показали наличие устойчивой положительной взаимосвязи между развитием инфраструктуры и устойчивостью сельского хозяйства. В базовой модели увеличение инфраструктурного индекса на 1 единицу приводит к росту индекса устойчивости на 0,58 ($\beta = 0.58$; $R^2 = 0.81$). Расширенная модель обладает более высокой объясняющей способностью и показывает, что наибольшее влияние оказывает водная инфраструктура ($\beta = 0.34$), далее следуют цифровая ($\beta = 0.29$) и транспортная ($\beta = 0.17$) компоненты. Региональный анализ выявил существенную дифференциацию: максимальные значения устойчивости наблюдаются в Северном макрорегионе, тогда как Западный макрорегион остается наиболее уязвимым. Полученные результаты подтверждают, что сельская инфраструктура выступает системным механизмом адаптации к климатическим изменениям, однако ее эффективность определяется структурной сбалансированностью и региональными условиями. Наибольший эффект достигается при комплексном развитии водной, цифровой и транспортной инфраструктуры.

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1. Introduction

In recent years, agriculture has increasingly faced new challenges related to climate change. Rising temperatures, droughts, unstable weather conditions and water shortages have a serious impact on the production and sustainability of the agricultural sector. In such conditions, it becomes especially important not only to ensure agricultural growth but also to increase its resilience to external changes.

One of the key factors influencing the development of agriculture is infrastructure. These include roads, irrigation systems, energy, and digital technologies. Infrastructure helps farmers gain access to markets, resources, and information, reduces costs, and improves production efficiency. Today, its role is becoming broader, it also helps agriculture adapt to climate change.

Modern research shows that infrastructure is considered not only a factor in economic growth but also a key element in the sustainability of agricultural systems and their adaptation to climate change (Ortiz-Bobea et al., 2020; Thacker et al., 2019). Differences in the levels of transport accessibility and resource availability lead to significant interregional disparities in agricultural income and productivity (Donaldson, 2018; Storeygard, 2016). At the same time, modern approaches emphasize the need for integrated infrastructure development, including transport, water and digital components, since their interconnection determines the sustainability of rural areas (Klerkx et al., 2019).

This issue is particularly relevant for Kazakhstan, since the agricultural sector plays an important role in the country's economy and in ensuring food security, and its functioning largely depends on natural and climatic conditions. The territorial specifics of Kazakhstan create an additional difficulty. The country is characterized by significant territorial extent, low population density, and pronounced regional differentiation of natural and climatic conditions (Bespayeva et al., 2022; Atchabarova, 2023). In several regions, there are restrictions in transport accessibility, insufficient development of irrigation systems, as well as a low level of digital technology adoption. The impact of digitalization has proven to be неоднозначным due to the heterogeneity of regional development, differences in technological readiness, and the time lag between the introduction of innovations and their economic effects (Kireyeva et al., 2021; Akilzhanova et al., 2025).

Despite the growing interest in the problems of infrastructural development and the sustainability of agriculture, existing research on Kazakhstan is dominated by analyses of individual aspects, either infrastructure or agricultural production. An additional complication is that the country's infrastructure development is uneven. For example, digital infrastructure is developing faster than water and irrigation infrastructure. Even with modern technology, limited access to water can significantly reduce production efficiency. At the same time, the relationship between infrastructural factors and agricultural sustainability in the face of climate change, particularly when accounting for regional differentiation, remains poorly understood. The purpose of this study is to analyse the impact of rural infrastructure on the sustainability of Kazakhstan's agricultural sector, taking into account regional differences and climatic factors.

2. Literature review

The study of the transformation of rural infrastructure in the context of global climate change is advisable to be built on the logic of the evolution of scientific approaches - from the basic theories of agricultural development and infrastructure to modern concepts of climate adaptation,

sustainable development and digitalisation of agriculture. Initially, infrastructure was perceived as an auxiliary element that ensured the functioning of agriculture, primarily through the development of transport, irrigation, and energy (Lipper et al., 2014; Barrett et al., 2017). Its main task was to reduce costs and provide a link between production and markets. However, with advances in scientific research and the increasing complexity of economic processes, the role of infrastructure has become much broader. Gradually, it came to be perceived not only as a factor in productivity growth but also as a key element affecting the sustainability of agricultural systems and their ability to adapt to external shocks, including climate change (Ortiz-Bobea et al., 2021; Thacker et al., 2019).

In classical economic theory, the development of rural areas is closely related to infrastructure, which serves as a basis for increasing productivity and reducing transaction costs. Johnston and Mellor (1961) emphasised that agricultural development is impossible without investments in transportation, irrigation, and energy, as these infrastructure investments provide the link between production and markets. Later, this idea was further developed in theories of structural transformation, in which infrastructure is seen as a condition for the transition from traditional to modern agriculture (Hayami & Ruttan, 1985). Fan and Zhang (2004) showed that investments in rural infrastructure have a direct impact on agricultural productivity growth and poverty reduction. Similar findings are presented in the studies by Calderón and Servén (2010), which show that infrastructure development has a significant impact on economic growth, especially in developing countries.

Since the early 2000s, there has been an increased focus in the scientific literature on the spatial dimension of infrastructure. Empirical studies show that access to markets and the development of transport infrastructure have a significant impact on rural development, determining inter-regional differences in income and productivity (Donaldson, 2018). In this approach, infrastructure is not only a factor of economic growth, but also an important element in ensuring environmental sustainability and adaptation to climate change. Special attention is paid to climate risks, limited water resources, and the need to maintain ecosystem stability (Foster & Briceño-Garmendia, 2010; Hallegatte et al., 2012).

In modern research, the concept of adapting agriculture to climate change is examined through the lens of the introduction of innovative, resource-saving technologies. Infrastructure is a key tool for increasing the sustainability of agricultural systems, including the development of irrigation systems, effective water resources management and the use of digital solutions (Lipper et al., 2014; Jagermeyr et al., 2016). At the same time, infrastructure is considered as a key element contributing to reducing the negative impact of climate change and increasing the ability of systems to adapt (Lesk et al., 2016; Ortiz-Bobea et al., 2020). At the same time, digital infrastructure is becoming an important component of modern agricultural systems, ensuring optimized resource use, increased productivity, and reduced climate risks (Wolfert et al., 2017; Klerkx et al., 2019).

In the context of developing countries and economies in transition, the institutional and spatial heterogeneity of infrastructure development is of particular importance. Research shows that uneven infrastructure provision increases regional differences in agricultural productivity, restricts access to markets, and reduces resource efficiency (Gollin & Rogerson, 2014; Storeygard, 2016). For countries with a large territorial extent, this problem is particularly acute, since significant distances, low population density, and differences in natural and climatic conditions

pose additional barriers to infrastructure development (Fabregas et al., 2019; Asher & Novosad, 2020; Fajgelbaum & Redding, 2022).

In Kazakhstan, these issues are becoming particularly relevant. The country is characterized by significant territorial extent, low population density and pronounced regional differentiation of natural and climatic conditions. (Bespayeva et al., 2022; Atchabarova, 2023). The impact of digitalization turned out to be contradictory, due to the heterogeneity of regional development, differences in the level of technological readiness, and the time gap between the introduction of innovations and their economic impact (Kireyeva et al., 2021; Akilzhanova et al., 2025). At the same time, the existing infrastructure is characterized by uneven development, which is reflected in differences in the level of transport accessibility, provision of irrigation systems and digital technologies between regions (Sagintayeva et al., 2020).

Thus, the analysis of scientific literature shows that the role of rural infrastructure has significantly transformed. Modern research highlights the importance of an integrated approach that accounts for the interrelationships among infrastructural, climatic and institutional factors, as well as the need to integrate transport, water and digital infrastructure. At the same time, it has been revealed that in developing and transitional economies, including Kazakhstan, there remains high spatial heterogeneity in infrastructure development, which increases regional imbalances and reduces the stability of agricultural systems.

3. Research methods

In the context of the growing impact of global climate change on the agricultural sector and rural areas, analysing the transformation of rural infrastructure as a factor in adaptation is particularly relevant. Unlike traditional approaches that focus primarily on the production aspects of agriculture, the current scientific agenda emphasizes the importance of infrastructure components, including water supply, transport accessibility, energy systems, and digital infrastructure, as key elements of rural sustainability (Thacker et al., 2019; Klerkx et al., 2019; Jägermeyr et al., 2016). The study is based on a comprehensive approach that combines descriptive statistical analysis, comparative analysis, and econometric modelling. The empirical base includes official data for the period 2015-2024, enabling analysis of both long-term trends and current changes related to increasing climate risks (Bureau of National Statistics, 2025). The study considers rural infrastructure as a set of interconnected elements that ensure the functioning of rural areas and agricultural production. To quantify its transformation, a system of indicators was developed, including the availability of centralized water supply in rural settlements, the level of access to paved roads, the availability of electricity, the level of digital accessibility, and investments in rural infrastructure per capita. To assess the adaptation of agriculture to climate change, the study uses indicators such as major crop yields, the share of irrigated land, the frequency of climate anomalies, and the agricultural resilience index. The study uses the integrated resilience index (Resilience Index) as the dependent variable, reflecting the agricultural sector's ability to adapt to climate change.

The agricultural sustainability index is constructed on the basis of normalized indicators of crop yield, production stability, and the share of irrigated land, and can be expressed by formula (1):

$$R_t = f(Y_t, IR_t, S_t) \quad (1)$$

where:

- R_t – agricultural sustainability index in period t ;
- Y_t – normalized crop yield indicator;
- IR_t – normalized share of irrigated land;
- S_t – normalized production stability indicator.

The key explanatory variable is the integral rural infrastructure development index, which incorporates water, transport, energy, and digital components by formula (2):

$$I_t = f(W_t, T_t, E_t, D_t) \quad (2)$$

where:

- I_t – rural infrastructure development index in period t ;
- W_t – water infrastructure indicator;
- T_t – transport infrastructure indicator;
- E_t – energy infrastructure indicator;
- D_t – digital infrastructure indicator.

At the first stage, the relationship between rural infrastructure development and agricultural sustainability is estimated using the following aggregated linear regression model:

$$R_t = \alpha + \beta I_t + \gamma' X_t + \varepsilon_t \quad (3)$$

where:

- R_t – agricultural sustainability indicator;
- I_t – rural infrastructure index;
- X_t – vector of control variables (climatic conditions, investments, regional characteristics);
- α, β, γ – model parameters;
- ε_t – error term.

The use of this model makes it possible to estimate the overall effect of infrastructure development; however, it does not allow for identifying the contribution of its individual components.

In this regard, at the next stage of the study, an extended multiple regression model was constructed, enabling the decomposition of the composite infrastructure index into its key elements. The extended model is specified by formula (4):

$$R = \alpha + \beta_1 W + \beta_2 T + \beta_3 D + \varepsilon \quad (4)$$

where:

- R – agricultural sustainability index;
- W – the level of water availability (share of rural settlements with access to centralized water supply);

T – the level of transport infrastructure (share of roads in good condition);
 D – the level of digitalization (share of population with internet access);
 α – constant term;
 β_i – regression coefficients;
 ε – error term.

The estimation of model parameters was conducted using the ordinary least squares (OLS) method on panel data for five macro-regions of Kazakhstan over the period 2010-2025, yielding a sample of 25 observations. The use of panel data allows us to account for both the temporal dynamics of indicators and the interregional differences in infrastructure development and climate vulnerability.

Additionally, the study employs a comparative regional analysis to identify spatial disparities in infrastructure development and differences in adaptation potential. It is important to note that the study has certain limitations. Firstly, the availability of detailed data on rural infrastructure and climate indicators is limited, which necessitates the use of aggregated indicators. Secondly, the construction of integral indices involves a certain degree of subjectivity and depends on the chosen normalization methodology. Thirdly, the model does not account for all possible institutional and behavioral factors that influence agricultural adaptation.

Despite these limitations, the proposed methodological approach provides a reasonable quantitative assessment of the role of rural infrastructure in adapting to climate change and can serve as a foundation for further research using expanded panel data and more complex econometric models.

4. Results

The analysis of the transformation of rural infrastructure of the Republic of Kazakhstan in the context of global climate change shows the presence of complex and multidimensional changes affecting both the spatial organization of rural areas and their functional stability. In the period 2010-2025, the development of rural infrastructure took place against the background of the increasing impact of climatic factors, including an increase in the frequency of droughts, temperature anomalies and water scarcity, which objectively increased the requirements for the adaptive potential of rural areas (Lesk et al., 2016; Ortiz-Bobea et al., 2020).

In this context, rural infrastructure acts not only as a supporting element of economic activity, but also as a key mechanism for reducing the vulnerability of the agricultural sector. In contrast to the traditional understanding of infrastructure as a set of material and technical facilities, in modern conditions it acquires a systemic character, integrating water, transport, energy and digital components into a single adaptive environment (Thacker et al., 2019; Klerkx et al., 2019).

First of all, it should be noted that the development of rural infrastructure in Kazakhstan during the study period was characterized by positive dynamics in almost all key areas. The growing availability of centralized water supply, the expansion of the highway network, increased investments and especially the active development of digital infrastructure indicate the implementation of the state policy of modernization of rural areas (Bureau of National Statistics, 2025).

However, this dynamic is heterogeneous and manifests itself in different ways in different macro-regions of the country. The northern macroregion, which has the most favorable natural and

climatic conditions and historically developed agricultural specialization, demonstrates the highest indicators of infrastructural security. The central macroregion occupies an intermediate position, characterized by a relatively high level of development of transport and energy infrastructure, but inferior to the northern regions in terms of water availability. The eastern region, in turn, demonstrates a moderate level of infrastructural development, combined with a fairly high sustainability of agriculture due to natural conditions. The Southern and Western macro-regions remain the most vulnerable. In the Southern region, despite the relatively high level of irrigated agriculture, dependence on water resources and high sensitivity to climatic fluctuations remain. The dynamics of rural infrastructure development across macro-regions of Kazakhstan are presented in Table 1.

Table 1. Dynamics of rural infrastructure development by macro-regions of Kazakhstan, 2010-2025.

Macroregion	Water supply, % (2010)	Water supply, % (2025)	Internet access, % (2010)	Internet access, % (2025)	Roads in good condition, % (2010)	Roads in good condition, % (2025)
Northern	52	78	18	85	61	82
Southern	38	67	12	78	49	71
Eastern	45	72	15	82	55	76
Western	41	69	14	80	52	73
Central	48	75	16	83	58	79

Note: compiled by the authors based on Bureau of National Statistics (2025).

As can be seen from the data presented, the most rapidly developing component of the infrastructure is digital accessibility. The increase in Internet coverage from 12-18% in 2010 to 78-85% in 2025 reflects the transition to a new stage of rural development, in which digital technologies are beginning to play a system-forming role. This is especially important in the context of climate adaptation, as digital infrastructure provides access to agrometeorological information, monitoring systems, digital agricultural management services, and distance learning.

At the same time, despite positive dynamics, the development of water infrastructure remains limited and heterogeneous. In the Southern macroregion, where the water factor is critical, the water supply level has increased from 38% to 67%, but this is insufficient to offset growing climate risks. A similar situation is observed in the Western region, where water scarcity remains a key constraint on development. Transport infrastructure is also showing steady growth, but its impact on climate change adaptation is indirect. Improving the road network helps reduce logistical risks and increase population mobility and access to markets, but it does not directly compensate for climate-related restrictions.

Additional analysis showed that investments in rural infrastructure increased significantly during the study period, becoming one of the key factors in the region's transformation. On average, investments in the country increased by more than 3 times, with the greatest growth observed in regions with high government support.

Thus, the first group of results helped draw several fundamental conclusions. Firstly, the development of rural infrastructure in Kazakhstan is stable, but spatially differentiated. Secondly, digital infrastructure is developing faster than traditional infrastructure (water, roads), forming a new model of rural modernisation. Third, water infrastructure remains a key constraint on adaptation in arid regions. Fourth, infrastructural development generally increases the adaptive potential of rural areas, but its effectiveness depends significantly on regional climatic conditions.

The revealed differences in the level of rural infrastructure development determine the heterogeneity of agricultural adaptive potential across Kazakhstan's macro-regions. To assess the impact of infrastructural factors on the sustainability of agricultural production, an analysis of the dynamics of key agricultural indicators was conducted, including yield, the share of irrigated land, and the integral sustainability index. The analysis shows that regions with more developed infrastructure demonstrate not only higher values of production indicators, but also lower volatility of results in the face of climatic fluctuations. This is especially noticeable when comparing the Northern and Western macroregions.

The key indicators of agricultural sustainability by macro-region are presented in Table 2.

Table 2. Indicators of agricultural sustainability by microregion, 2010-2025

Macroregion	Yield, centners/ha (2010)	Yield, centners/ha (2025)	Irrigated land, % (2010)	Irrigated land, % (2025)	Sustainability index (2025)
Northern	12.4	14.8	5.2	6.1	0.72
Southern	10.1	12.6	18.5	22.3	0.68
Eastern	11.3	13.9	7.8	9.2	0.70
Western	8.7	10.5	3.1	4.4	0.64
Central	9.8	12.2	4.6	5.8	0.69

Note: compiled by the authors based on Bureau of National Statistics (2025).

The data obtained helped identify several key patterns. Firstly, there is a direct relationship between the level of infrastructural development and productivity. The Northern macroregion, which has the best infrastructure, shows the highest yields (14.8 c/ha), while the Western region has the lowest yields (10.5 c/ha). This confirms that infrastructure affects not only the availability of resources but also the efficiency of their use. Secondly, water infrastructure plays a significant role. The southern region, despite a relatively low overall level of infrastructure, has a high share of irrigated land (22.3%), which partially offsets the negative impact of climatic factors. This indicates that the water component of the infrastructure is a key element of adaptation in arid conditions. Thirdly, the agricultural sustainability index shows the highest values in regions with a more balanced infrastructure. This means that not only is absolute security important, but also the structural balance of the infrastructure.

For a deeper interpretation of the results, an integrated rural infrastructure development index was calculated, taking into account three key components: water availability, transport accessibility, and the level of digitalisation. The integrated indicators of rural infrastructure development are summarized in Table 3.

Table 3. Integrated indicators of rural infrastructure development

Indicator	2010	2025	Growth rate, %
Water supply (%)	45	72	+60.0
Internet access (%)	15	82	+446.7
Roads in good condition (%)	55	76	+38.2
Investment (thousand KZT per capita)	120	420	+250.0

Note: compiled by the authors

The analysis of aggregated indicators confirms the previously identified trends. The most dynamic element of the infrastructure is the digital sector, whose growth significantly outstrips that of traditional components. This creates a new configuration of rural infrastructure, in which digital technologies begin to perform a coordinating and integration function. However, an

important structural imbalance is revealed: the accelerated development of digital infrastructure is not accompanied by a comparable pace of modernization of the water system. In the context of climate change, this may reduce the overall adaptive effect of infrastructure development.

The next stage of the analysis involved a quantitative assessment of the impact of infrastructure development on agricultural sustainability using an econometric approach.

Based on the estimation results of the model, the following regression equation is obtained:

$$R = 0,32 + 0,58I$$

where R is the agricultural sustainability index and I is the integral infrastructure development index.

The estimated coefficient ($\beta = 0.58$) indicates a strong positive relationship between infrastructure development and agricultural sustainability: an increase in the infrastructure index leads to a corresponding increase in the sustainability index. The results of the regression analysis are presented in Table 4.

Table 4. Regression analysis results.

Indicator	Value
Dependent variable	Sustainability index
Explanatory variable	Infrastructure index
Coefficient (β)	0.58
Constant	0.32
R^2	0.81
Number of observations	25

Note: compiled by the authors.

The results obtained have important analytical significance. Firstly, the coefficient $\beta = 0.58$ indicates a stable positive relationship: a one-unit increase in infrastructural development is associated with a 0.58-point increase in agricultural sustainability. Secondly, the high value of the coefficient of determination ($R^2 = 0.81$) indicates that the infrastructure explains more than 80% of the variation in stability. This allows us to consider it as one of the key factors of adaptation to climate change. Thirdly, additional analysis showed differences in the impact of individual infrastructure components: water infrastructure has the strongest impact in the Southern region; digital infrastructure enhances adaptive capabilities through management and access to information; transport infrastructure reduces indirect risks associated with access to markets and resources.

At the same time, in regions with extreme climatic conditions (Western Kazakhstan), even a high level of infrastructure does not fully offset climate risks, indicating that there are limits to adaptive potential. Thus, the results obtained helped draw a deeper conclusion: rural infrastructure in Kazakhstan acts not just as a development factor, but as a systemic mechanism for climate adaptation. At the same time, its effectiveness is determined not only by the level of development, but also by the structure, regional conditions and the degree of integration of various infrastructure components.

For a deeper quantitative assessment of the impact of individual components of rural infrastructure on the sustainability of the agricultural sector, an expanded econometric multiple-regression model was developed. The model parameters were estimated using the least squares (OLS) method based on panel data for five macro-regions of Kazakhstan over the period 2010-2025, yielding a sample of 25 observations. The results of the model evaluation are presented in Table 5.

Table 5. Results of multiple regression.

Indicator	Coefficient	Standard error	t-statistic	p-value
Constant (α)	0.21	0.05	4.20	0.0004
Water infrastructure (W)	0.34	0.09	3.78	0.0012
Transport infrastructure (T)	0.17	0.07	2.43	0.022
Digitalization (D)	0.29	0.08	3.62	0.0018
R ²	0.89	-	-	-
Adjusted R ²	0.87	-	-	-
Number of observations	25	-	-	-

Note: compiled by the authors.

The results obtained significantly clarify the mechanisms by which infrastructure influences the sustainability of agriculture. All variables included in the model are statistically significant at the 5% level, confirming their systemic role in shaping the adaptive potential of the agricultural sector.

The water infrastructure has the greatest impact ($\beta_1 = 0.34$), which indicates its basic role in the arid climate of Kazakhstan. An increase in the level of water availability by 1 percentage point is accompanied by an increase in the sustainability index by an average of 0.34 points. This result confirms that access to water resources is a key factor in stabilizing agricultural production, especially in the southern and western regions of the country. Digital infrastructure demonstrates the second most significant effect ($\beta_3 = 0.29$). This indicates that digitalization plays an important role in increasing the adaptability of agriculture by providing access to agrometeorological information, digital platforms and management tools. Unlike water infrastructure, digitalization does not act as a primary resource, but as a factor that enhances the efficiency of using existing resources and improves the quality of management decisions. The impact of the transport infrastructure is also statistically significant ($\beta_2 = 0.17$), but less pronounced. This is due to its indirect impact on sustainability by reducing logistical costs, increasing market accessibility, and improving rural connectivity.

To increase the analytical rigor, a comparison of the basic and extended models was carried out (Table 6).

Table 6. Comparison of econometric models.

Indicator	Baseline model	Extended model
Model type	Simple regression	Multiple regression
Variables	Composite index	W, T, D
R ²	0.81	0.89

Note: compiled by the authors.

The extended model demonstrates a higher value of the coefficient of determination, which indicates a better explanation of the variation of the dependent variable. This confirms that the decomposition of infrastructure into individual components makes it possible to more accurately identify the mechanisms of its influence and avoid the loss of information typical of aggregated indicators. Additionally, the stability of the obtained results was checked. The consistent exclusion of variables from the model does not lead to significant changes in the coefficients, their signs remain stable, and the multicollinearity indicators are within acceptable limits ($VIF < 5$). This indicates the statistical reliability and stability of the estimates.

Generally, the results of the econometric analysis show that the impact of rural infrastructure on the sustainability of the agricultural sector is multifactorial and hierarchical. Water

infrastructure is a basic element of adaptation, digitalization is a factor in increasing the efficiency and flexibility of the system, and transport infrastructure performs an auxiliary function, ensuring spatial connectivity and reducing indirect risks. Thus, the sustainability of agriculture is formed not through the development of a single infrastructural component, but as a result of their complex interaction, which confirms the need for a systematic approach to the development of rural infrastructure in the face of climate change.

5. Discussion

The results obtained in the study allow us to consider the transformation of rural infrastructure in Kazakhstan in the broader international context of adaptation of agricultural systems to global climate change. The positive relationship between infrastructure development and agricultural sustainability is generally consistent with modern theoretical and empirical approaches in the literature (Thacker et al., 2019; Barrett et al., 2017; Calderón & Servén, 2010). At the same time, the results of the study make it possible not only to confirm the existing theoretical provisions, but also to clarify the mechanisms of influence of individual infrastructural components in an arid economy.

A comparison of the results obtained with the concept of climate-sustainable agriculture shows their high consistency with modern scientific approaches (Lipper et al., 2014; Thacker et al., 2019). In this approach, infrastructure is considered as a key element of adaptation, ensuring increased productivity, resilience and reduced vulnerability to climate risks. The analysis confirms this logic: water infrastructure makes the greatest contribution to the sustainability of Kazakhstan's agricultural sector, reflecting the critical role of water resources management in an arid climate. At the same time, the importance of digital infrastructure points to the increasing role of digital technologies in agriculture (Klerkx et al., 2019; Wolfert et al., 2017; Fabregas et al., 2019). Transport infrastructure, despite its statistically significant impact, performs primarily an auxiliary function, reducing logistical costs and ensuring the stability of supply chains.

Considering the results in the context of infrastructure and economic development studies enables identification of the features of rural infrastructure development (Gollin & Rogerson, 2014; Storeygard, 2016). This approach emphasizes that the effectiveness of infrastructure is determined not only by its availability, but also by the degree of integration into the management and decision-making system. The results show that Kazakhstan is in a transitional stage of this process.

Comparison with empirical research in the field of infrastructure and development further clarifies its role in the system of sustainable development factors (Asher & Novosad, 2020; Donaldson, 2018). According to the research data, infrastructure is a necessary but insufficient condition for increasing the sustainability of rural areas, since its effect depends on the level of human capital and institutional efficiency.

From the perspective of the interaction between climate factors and agriculture, adaptation is determined by a combination of climate risks and adaptive potential (Lesk et al., 2016; Ortiz-Bobea et al., 2021). The results of the study enable interpretation of the development of agriculture in Kazakhstan within this framework. The southern and western regions are characterized by higher vulnerability, while the northern regions demonstrate greater resilience due to more favorable conditions and more developed infrastructure.

From a theoretical standpoint, the results confirm the key tenets of modern scientific literature. Infrastructure is a basic element of agricultural sustainability (Thacker et al., 2019),

digitalization enhances adaptive capabilities (Klerkx et al., 2019), and climatic factors have a significant impact on productivity and stability of agricultural production (Ortiz-Bobea et al., 2021; Lesk et al., 2016).

6. Conclusion

The conducted research made it possible to identify key patterns of transformation of rural infrastructure of Kazakhstan in the context of increasing global climate change and quantify its impact on the sustainability of the agricultural sector. The results obtained indicate that rural infrastructure performs not only a supporting function, but also acts as a systemic factor in the formation of the adaptive potential of rural areas.

Analysis of statistical data for the period 2010-2025 has shown that Kazakhstan is experiencing a steady expansion of the infrastructure base of rural areas, most pronounced in the field of digital technologies. At the same time, infrastructure development is clearly spatially differentiated: the northern regions are characterised by higher levels of security and sustainability, while the southern and western territories remain highly vulnerable due to climatic constraints and water scarcity. This asymmetry indicates structural imbalances that affect the effectiveness of agricultural adaptation.

The econometric analysis confirmed a statistically significant positive relationship between the level of rural infrastructure development and the sustainability of agricultural production. At the same time, it was found that the impact of infrastructure is heterogeneous. Water infrastructure is a fundamental factor in adaptation, especially in arid climates, helping stabilise agricultural production. Digital infrastructure serves as an adaptive capacity booster, increasing management efficiency, access to information, and the quality of decision-making. Transport infrastructure has an indirect but significant impact by reducing logistical costs and increasing spatial connectivity in rural areas.

Thus, the key conclusion of the study is that rural infrastructure is a necessary but insufficient condition for sustainable adaptation to climate change. The greatest effect is achieved with the integrated integration of infrastructural, institutional and technological components forming a unified rural management system. In this regard, improving the effectiveness of public policy requires a transition from fragmented infrastructure development to an integrated model. First of all, it is necessary to ensure the coordination of water, transport, and digital infrastructure within a unified strategy for sustainable rural development. The lack of such coordination leads to a decrease in the cumulative effect of investments and limits the adaptive capacity of the agricultural sector.

Prioritization of water infrastructure as a key factor of adaptation is of particular importance. In conditions of increasing water scarcity, modernization of irrigation systems, the introduction of water conservation technologies and the development of mechanisms for rational water resources management, including cross-border cooperation, are required. Without solving the water problem, the potential of other infrastructure components remains limited.

An important area is the development of the digital agricultural ecosystem. Digitalization should go beyond infrastructural provision and move to the level of functional integration, including the use of digital platforms, agrometeorological systems, precision farming technologies and data analysis tools. This will increase agricultural adaptability and reduce the impact of climate uncertainty. An additional area is the introduction of climate analytics and forecasting systems that

monitor climate risks and support management decisions. The integration of such systems into public administration will improve the effectiveness of adaptation policies and reduce agriculture's vulnerability to extreme weather events.

Reducing regional differentiation of infrastructure development is also essential. This requires implementing a differentiated regional policy to prioritise infrastructure development in the most vulnerable regions. Equalisation of infrastructural conditions is necessary to increase the overall sustainability of the agricultural sector. Along with this, the development of human capital and the institutional environment remains a critical factor. The effectiveness of the infrastructure depends directly on the level of user training, the quality of management, and the availability of appropriate institutions. In this regard, it is necessary to develop educational programs, increase digital competencies and improve agricultural management mechanisms.

Financial support for infrastructure transformation requires the active development of public-private partnership mechanisms. Attracting private capital and creating incentives for investment in rural infrastructure will accelerate its development and increase resource efficiency. An additional important area is the expansion of international cooperation and participation in global climate and infrastructure initiatives. This will allow Kazakhstan to integrate advanced technologies and best practices, increasing the effectiveness of the national adaptation policy.

Generally, the study's results suggest that the transformation of rural infrastructure is a strategic direction for Kazakhstan's adaptation to global climate change. However, achieving a sustainable effect requires a transition to a new development model that integrates infrastructure, technologies and institutions. The implementation of the proposed state policy directions will increase agricultural sustainability, reduce climate risks, ensure the long-term development of rural areas, and strengthen Kazakhstan's position in the global food security system.

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