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Kazakh National Agrarian Research University, Almaty, Kazakhstan.

E-mail: Raxat_a@mail.ru

DIGITAL INEQUALITY AND AGRICULTURAL PRODUCTIVITY: EVIDENCE FROM SOUTHERN KAZAKHSTAN

Naimanova Zhulduz — PhD student, Kazakh National Agrarian Research University, Kazakhstan,
E-mail: dayana_m2009@mail.ru, ORCID: <https://orcid.org/0000-0002-7830-7133>;

Bakirbekova Aigul — candidate of Economic Sciences, Professor, Kazakh National Agrarian Research University, Kazakhstan,

E-mail: aigul.bakirbek@mail.ru, ORCID: <https://orcid.org/0000-0002-0981-8306>;

Kuralbayeva Roza — PhD in Economics, senior lecturer, Kazakh National Agrarian Research University, Kazakhstan,

E-mail: Raxat_a@mail.ru, ORCID: <https://orcid.org/0009-0009-2661-1102>.

Abstract. This paper examines digital inequality in agriculture and its economic implications for the agricultural sector in the southern regions of Kazakhstan. The relevance of the study is driven by the need to assess the role of digital technologies in improving productivity and sustainability in agriculture under increasing climate and resource constraints. The main objective is to provide a quantitative assessment of digital inequality and evaluate its impact on agricultural economic performance at the regional level. The methodological framework is based on endogenous growth theory and the concept of digital capital. The study employs econometric techniques, including panel data models (OLS, fixed effects, and random effects), as well as the construction of a composite Digital Inequality Index. The empirical dataset covers the period 2015–2025 and includes regional data from Almaty, Zhambyl, Turkestan, and Kyzylorda regions of Kazakhstan. The results reveal significant regional disparities in the level of digitalization in agriculture. The analysis confirms that digital inequality has a statistically significant impact on gross agricultural value added. Furthermore, the findings indicate that the relationship between digitalization and economic performance is both structural and nonlinear, with the strongest effects observed after reaching a certain threshold of digital development. The estimation of the economic cost of digital inequality

shows substantial losses in agricultural output due to limited access to digital technologies. The scientific contribution of the study lies in the development of a composite index for measuring digital inequality and in providing a quantitative evaluation of its economic effects. The results demonstrate that digital inequality is not only a technological issue but also a key economic constraint affecting productivity and growth in agriculture. From a policy perspective, the findings highlight the importance of reducing digital disparities through targeted regional strategies, improved access to digital infrastructure, and enhanced adoption of digital technologies in agriculture. The study contributes to the broader literature on digital transformation in developing economies and provides a foundation for designing more inclusive and effective digital policies in the agro-industrial sector.

Keywords. digital inequality, agriculture, digitalization, agro-industrial complex, economic assessment, digital infrastructure, ICT

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Қазақ ұлттық аграрлық зерттеу университеті, Алматы, Қазақстан.

E-mail: Raxat_a@mail.ru

ЦИФРЛЫҚ ТЕҢСІЗДІК ЖӘНЕ АУЫЛ ШАРУАШЫЛЫҒЫНЫҢ ӨНІМДІЛІГІ: ОҢТҮСТІК ҚАЗАҚСТАННАН АЛЫНҒАН ДЕРЕКТЕР

Найманова Жұлдыз — PhD докторант, Қазақ ұлттық аграрлық зерттеу университеті, Алматы, Қазақстан,

E-mail: dayana_m2009@mail.ru, ORCID: <https://orcid.org/0000-0002-7830-7133>;

Бакирбекова Айгүль — э. ф. к., профессор, Қазақ ұлттық ұлттық аграрлық зерттеу университеті, Алматы, Қазақстан,

E-mail: aigul.bakirbek@mail.ru, ORCID: <https://orcid.org/0000-0002-0981-8306>;

Құралбаева Роза — PhD доктор, Қазақ ұлттық ұлттық аграрлық зерттеу университеті, Алматы, Қазақстан,

E-mail: Raxat_a@mail.ru, ORCID: <https://orcid.org/0009-0009-2661-1102>.

Аннотация. Мақалада ауыл шаруашылығындағы цифрлық теңсіздік және оның Қазақстанның оңтүстік өңірлеріндегі аграрлық сектордың экономикалық нәтижелеріне әсері қарастырылады. Зерттеудің өзектілігі цифрлық технологиялардың өнімділікті арттырудағы және климаттық әрі ресурстық шектеулер жағдайында ауыл шаруашылығының тұрақтылығын қамтамасыз етудегі рөлін бағалау қажеттілігімен анықталады. Зерттеудің мақсаты – цифрлық теңсіздікті сандық тұрғыда бағалау және оның ауыл шаруашылығына тигізетін экономикалық әсерін аймақтық деңгейде анықтау.



Зерттеудің әдіснамалық негізі эндогендік экономикалық өсу теориясына және цифрлық капитал тұжырымдамасына сүйенеді. Жұмыста эконометрикалық талдау әдістері, соның ішінде панельдік модельдер (OLS, бекітілген және кездейсоқ әсерлер), сондай-ақ цифрлық теңсіздіктің интегралдық индексі құру әдісі қолданылды. Эмпирикалық база 2015–2025 жылдар аралығындағы Қазақстан Республикасының ресми статистикалық деректеріне негізделіп, Алматы, Жамбыл, Түркістан және Қызылорда облыстарын қамтиды. Зерттеу нәтижелері ауыл шаруашылығындағы цифрландыру деңгейінде айтарлықтай аймақтық айырмашылықтардың бар екенін көрсетеді. Цифрлық теңсіздіктің аграрлық сектордың қосылған құнына статистикалық тұрғыдан маңызды әсер ететіні анықталды. Сонымен қатар әсердің құрылымдық және сызықтық емес сипаты айқындалды, яғни экономикалық тиімділік цифрлық даму белгілі бір деңгейге жеткенде күшейеді. Цифрлық теңсіздіктің «экономикалық құнын» бағалау цифрлық технологияларға қолжетімділіктің шектеулі болуына байланысты өнімнің едәуір жоғалуын көрсетеді. Зерттеудің ғылыми жаңалығы цифрлық теңсіздіктің интегралдық индексі әзірлеуде және оның экономикалық әсерін сандық тұрғыда бағалауда көрінеді. Практикалық маңыздылығы нәтижелерді агроөнеркәсіптік кешенді цифрландыру саясатын жетілдіруде және аймақтық теңсіздіктерді азайтуда қолдану мүмкіндігімен сипатталады.

Түйін сөздер: цифрлық теңсіздік, ауыл шаруашылығы, цифрландыру, агроөнеркәсіптік кешен, экономикалық бағалау, цифрлық инфрақұрылым, АКТ

© **Найманова Ж., Бакирбекова А., Куралбаева Р.***, 2026.

Казахский национальный аграрный исследовательский университет,

Алматы, Казахстан.

E-mail: Raxat_a@mail.ru

ЦИФРОВОЕ НЕРАВЕНСТВО И ПРОДУКТИВНОСТЬ СЕЛЬСКОГО ХОЗЯЙСТВА: ДАННЫЕ ИЗ ЮЖНОГО КАЗАХСТАНА

Найманова Жулдыз — докторант PhD, Казахский национальный аграрный исследовательский университет, Казахстан,

E-mail: dayana_m2009@mail.ru, ORCID: <https://orcid.org/0000-0002-7830-7133>;

Бакирбекова Айгуль — кандидат экономических наук, профессор, Казахский национальный аграрный исследовательский университет, Казахстан,

E-mail: aigul.bakirbek@mail.ru, ORCID: <https://orcid.org/0000-0002-0981-8306>;

Куралбаева Роза — PhD доктор, Казахский национальный аграрный исследовательский университет, Казахстан,

E-mail: Raxat_a@mail.ru, ORCID: <https://orcid.org/0009-0009-2661-1102>.

Аннотация. В статье исследуется цифровое неравенство в сельском хозяйстве и его влияние на экономические результаты аграрного сектора Южного региона Казахстана. Актуальность исследования обусловлена

необходимостью оценки роли цифровых технологий как фактора повышения производительности и устойчивости аграрного производства в условиях усиливающихся климатических и ресурсных ограничений. Целью работы является количественная оценка цифрового неравенства и определение его экономических последствий для сельского хозяйства на региональном уровне. Методологическая основа исследования базируется на теории эндогенного экономического роста и концепции цифрового капитала. В работе применяются методы эконометрического анализа, включая панельные модели (OLS, фиксированные и случайные эффекты), а также построение интегрального индекса цифрового неравенства. Эмпирическая база сформирована на основе официальных статистических данных Республики Казахстан за период 2015–2025 гг. по регионам Алматинской, Жамбылской, Туркестанской и Кызылординской областей. Результаты исследования показывают наличие значительных региональных диспропорций в уровне цифровизации сельского хозяйства. Установлено, что цифровое неравенство оказывает статистически значимое влияние на валовую добавленную стоимость аграрного сектора. Выявлена структурная и нелинейная природа данного влияния, при которой наибольший экономический эффект достигается при достижении определённого уровня цифрового развития. Оценка «стоимости» цифрового неравенства показывает наличие значительных потерь продукции, обусловленных ограниченным доступом к цифровым технологиям. Научная новизна исследования заключается в разработке интегрального индекса цифрового неравенства и количественной оценке его экономического эффекта. Практическая значимость работы определяется возможностью использования результатов при разработке региональной политики цифровизации агропромышленного комплекса и сокращения цифрового разрыва.

Ключевые слова: цифровое неравенство, сельское хозяйство, цифровизация, агропромышленный комплекс, экономическая оценка, цифровая инфра-структура, ИКТ

Introduction. In the context of the accelerating transition toward a digital economy, the agricultural sector is undergoing profound structural transformations driven by the widespread adoption of information and communication technologies (ICT), big data analytics, and digital platforms. Digitalization is increasingly recognized not merely as a technological upgrade, but as a systemic factor that enhances productivity, optimizes resource allocation, and strengthens the resilience and sustainability of agricultural systems, particularly under intensifying climate risks and global food security challenges (FAO, 2022; World Bank, 2021).

However, the diffusion of digital technologies in agriculture is inherently uneven, giving rise to a persistent and multidimensional phenomenon of digital inequality. In this context, digital inequality refers not only to disparities in access to digital infrastructure, but also to differences in the capacity to effectively utilize

digital tools, platforms, and data-driven solutions. In the agricultural sector, such disparities are reflected in unequal access to broadband connectivity, precision farming technologies, digital advisory services, and online market integration. As a result, a significant share of agricultural producers remains excluded from the benefits of digital transformation, which constrains productivity growth, limits efficiency gains, and reduces income potential (OECD, 2020; ITU, 2023).

From a theoretical standpoint, digitalization can be conceptualized as a form of capital deepening that contributes to total factor productivity (TFP) growth. Within the framework of endogenous growth theory, investments in digital technologies stimulate knowledge accumulation, accelerate innovation diffusion, and generate positive spillover effects across sectors (Romer, 1990; Aghion & Howitt, 1992). These mechanisms are particularly relevant for agriculture, a sector characterized by high sensitivity to information asymmetries, climatic variability, and resource constraints. By enabling data-driven decision-making, reducing transaction costs, and facilitating integration into modern value chains, digital technologies act as a critical driver of structural transformation in the agro-industrial complex (World Bank, 2019).

Despite these theoretical advantages, the digital transformation of agriculture in developing and transition economies remains uneven and fragmented. In Kazakhstan, although significant policy efforts have been undertaken through national initiatives such as the “Digital Kazakhstan” program, substantial regional disparities persist in terms of digital infrastructure, access to services, and technological adoption. Rural areas, in particular, continue to face constraints related to limited broadband coverage, insufficient digital skills, and institutional barriers to technology diffusion (Ministry of Digital Development of the Republic of Kazakhstan, 2023).

These challenges are especially pronounced in the southern regions of Kazakhstan—Almaty, Zhambyl, Turkestan, and Kyzylorda—which play a strategically important role in national agricultural production. The regions are characterized by a high concentration of crop farming, livestock production, and irrigated agriculture, while simultaneously exhibiting significant heterogeneity in economic development, infrastructural endowment, and digital readiness. This heterogeneity creates uneven conditions for technological adoption and contributes to differentiated productivity outcomes across regions (Bureau of National Statistics, 2025).

Although the existing body of literature provides valuable insights into the role of digitalization in agriculture—primarily focusing on technology adoption, productivity effects, and policy frameworks (FAO, 2022; OECD, 2020)—there remains a critical gap in empirical research that quantitatively evaluates digital inequality and its economic implications at the regional level, particularly in the context of Kazakhstan. Notably, the economic cost of digital inequality, expressed in terms of foregone output, unrealized productivity gains, and inefficiencies in resource use, has received limited scholarly attention.

Against this background, the present study aims to provide a comprehensive economic assessment of digital inequality in agriculture and to identify key pathways

for its reduction, using the southern regions of Kazakhstan as an empirical case. The contribution of this study is threefold. First, it develops a quantitative framework for measuring digital inequality in the agricultural sector. Second, it applies econometric modeling to estimate the impact of digital disparities on productivity and output. Third, it formulates evidence-based policy recommendations aimed at reducing digital inequality and enhancing the efficiency and competitiveness of the agro-industrial sector.

Literature Review. The study of digitalization as a driver of economic transformation in agriculture can be situated within the broader evolution of economic growth theories, ranging from neoclassical frameworks to contemporary approaches emphasizing knowledge, innovation, and digital ecosystems. This theoretical progression reflects a fundamental shift in the understanding of technology—from an exogenous factor of production to a central mechanism shaping productivity dynamics, structural change, and long-term economic development.

In classical and neoclassical growth theory, technological progress is treated as an exogenous variable. The Solow growth model (Solow, 1956) attributes long-term economic growth primarily to technological change that enhances productivity independently of capital and labor accumulation. While this framework provides a foundational understanding of growth dynamics, it fails to explain the endogenous mechanisms underlying technological advancement. This limitation was addressed by endogenous growth theory, which conceptualizes technological progress as the result of deliberate investments in knowledge, human capital, and innovation (Romer, 1990; Aghion & Howitt, 1992). Within this paradigm, digital technologies can be interpreted as a form of knowledge capital that enhances total factor productivity (TFP) and generates significant spillover effects across sectors.

The emergence of the digital economy has further expanded this theoretical perspective. Digitalization is increasingly understood as a systemic and transformative process involving the integration of digital technologies into economic and social systems, leading to new modes of value creation, coordination, and governance (Brynjolfsson & McAfee, 2014). Unlike traditional technologies, digital innovations are characterized by scalability, low marginal costs, and strong network externalities, which amplify their economic impact and accelerate diffusion processes (Varian et al., 2019). These characteristics make digital technologies particularly influential in sectors such as agriculture, where efficiency gains are closely tied to information flows, resource optimization, and risk management.

A growing body of empirical literature confirms that digitalization contributes to economic growth through multiple channels, including improvements in total factor productivity, reductions in transaction costs, and acceleration of innovation processes (Corrado et al., 2016; Goldfarb & Tucker, 2019). In agriculture, these mechanisms are especially relevant due to the sector's dependence on climatic variability, spatial heterogeneity, and information asymmetries. Digital tools such as remote sensing, precision agriculture, and data-driven decision support systems

enable more efficient input use, reduce uncertainty, and enhance yield performance (FAO, 2022).

However, the diffusion of digital technologies remains uneven, giving rise to the phenomenon of digital inequality. Contemporary literature extends the concept of the “digital divide” beyond mere access to infrastructure, emphasizing disparities in usage, skills, and the capacity to derive economic benefits from digital technologies (van Dijk, 2020). In agriculture, digital inequality manifests across multiple dimensions, including disparities between large and small-scale farms, rural and urban areas, and regions with differing levels of infrastructure and institutional support. Consequently, digital inequality not only limits the adoption of technologies but also reinforces existing structural imbalances within the agricultural sector.

Empirical evidence from international organizations highlights the persistence of digital inequality, particularly in developing and transition economies. Studies by the OECD (2020) and ITU (2023) demonstrate that limited access to broadband infrastructure, digital services, and human capital significantly constrains the adoption of advanced technologies in rural areas. This constraint is especially critical in agriculture, where digital technologies have the potential to reduce informational asymmetries, improve market access, and enhance value chain integration. In the absence of adequate digital access, agricultural producers remain excluded from modern market systems, resulting in lower productivity and income levels.

Importantly, recent research conceptualizes digital inequality not only as a technological issue but also as an economic and institutional phenomenon. The effectiveness of digitalization depends on complementary factors such as human capital, institutional quality, regulatory frameworks, and access to finance (Acemoglu et al., 2005; World Bank, 2021). In environments characterized by weak institutional capacity or low levels of education, the returns to digital investments may be significantly constrained. This underscores the necessity of adopting a systemic approach to digital transformation that integrates infrastructure development with institutional and human capital improvements.

Another critical dimension highlighted in the literature is the nonlinear nature of the relationship between digitalization and economic outcomes. Empirical studies suggest the existence of threshold effects, whereby the impact of digital technologies becomes significant only after reaching a certain level of development (Czernich et al., 2011). At early stages, investments in digital infrastructure may yield limited returns; however, once critical thresholds are surpassed, network effects and complementarities generate substantial productivity gains. Such nonlinear dynamics are particularly relevant in agriculture, where effective digital adoption requires a minimum level of infrastructure, technological readiness, and institutional support.

In the context of developing economies, digitalization is often framed as a potential mechanism for “leapfrogging,” enabling countries to bypass traditional development stages and accelerate structural transformation (UNCTAD, 2019).

In agriculture, mobile technologies and digital platforms can enhance access to information, financial services, and markets, thereby improving productivity and resilience. Nevertheless, the realization of these benefits is contingent upon reducing digital inequality and establishing enabling institutional environments.

Despite the rapid expansion of research on agricultural digitalization, the existing literature remains largely focused on technology adoption, productivity effects, and policy frameworks (FAO, 2022; OECD, 2020). Relatively limited attention has been paid to the quantitative assessment of digital inequality and its economic implications, particularly at the regional level. In particular, the concept of the economic cost of digital inequality—defined in terms of foregone output, unrealized productivity gains, and inefficiencies in resource allocation—remains insufficiently explored.

In Kazakhstan, the literature on digitalization in agriculture is still in its formative stage. While national initiatives such as the “Digital Kazakhstan” program have contributed to improvements in digital infrastructure and ICT adoption, significant regional disparities persist, particularly between urban and rural areas (Ministry of Digital Development of the Republic of Kazakhstan, 2023). The southern regions of Kazakhstan, characterized by intensive agricultural activity, face specific structural challenges related to infrastructure availability, water resource management, and access to advanced technologies.

Existing studies on Kazakhstan’s agricultural sector predominantly focus on productivity dynamics, structural transformation, and policy interventions, with limited emphasis on digital inequality. Although some research acknowledges the role of digital technologies in enhancing agricultural performance, comprehensive empirical analyses quantifying the impact of digital disparities on economic outcomes remain scarce. In particular, there is a notable absence of studies that estimate the economic losses associated with digital inequality at the regional level.

This research gap is particularly significant given the strategic importance of agriculture for Kazakhstan’s economic development and food security. A deeper understanding of digital inequality is essential for designing effective and inclusive digital policies that enhance the competitiveness and sustainability of the agro-industrial sector.

In response to these gaps, the present study contributes to the literature by developing a quantitative framework for assessing digital inequality in agriculture and estimating its economic impact using regional data from the southern regions of Kazakhstan. By integrating econometric modeling with regional analysis, the study provides new insights into the structural and economic dimensions of digital disparities and offers evidence-based policy recommendations aimed at reducing digital inequality and promoting inclusive digital transformation.

Materials and Methods. The quantitative assessment of digital inequality in agriculture requires a robust methodological framework capable of capturing both the multidimensional nature of digitalization and its economic implications. To address this complexity, the present study employs an integrated econometric

approach that combines panel data modeling, composite index construction, and scenario-based estimation. This framework enables a comprehensive evaluation of the impact of digital inequality on agricultural performance across the southern regions of Kazakhstan.

The methodological foundation of the study is grounded in endogenous growth theory, where technological progress-proxied by the adoption and diffusion of digital technologies-is treated as an internal driver of productivity and efficiency. Within this framework, digital inequality is conceptualized as an uneven distribution of digital capital, which generates disparities in production outcomes across regions and economic agents. Thus, variations in digital access and usage are expected to translate into measurable differences in agricultural output and efficiency.

The empirical analysis is based on a balanced regional panel dataset covering the period 2015–2025 for the southern regions of Kazakhstan, including Almaty, Zhambyl, Turkestan, and Kyzylorda. The dataset is compiled using official statistics from the Bureau of National Statistics of the Republic of Kazakhstan, the Ministry of Agriculture, and international sources such as the World Bank and the International Telecommunication Union (ITU). The panel structure allows for the simultaneous estimation of temporal dynamics and cross-sectional heterogeneity, which is essential for capturing spatial disparities in digital development.

A central component of the methodology is the construction of a composite Digital Inequality Index (DII), designed to quantify disparities in access to and utilization of digital technologies in agriculture. The index integrates multiple dimensions of digitalization, including infrastructure availability, technological adoption, and digital integration into economic activities:

$$DII_{it} = \sum_{k=1}^n w_k \cdot Z_{kit}$$

where Z_{kit} represents standardized indicators of digital development for region i in year t , and w_k denotes the corresponding weights assigned to each component. The index incorporates variables such as rural internet penetration, broadband availability, adoption of digital agricultural technologies, and access to digital services. All indicators are standardized using z-scores to ensure comparability and eliminate scale effects.

To quantify the extent of digital inequality, dispersion-based measures are derived from the DII, including the coefficient of variation and inter-regional disparity indices. These measures allow for the identification of regions with relatively low levels of digital development and provide a quantitative assessment of spatial inequality across the sample.

The core empirical model evaluates the impact of digital inequality on agricultural economic performance. Agricultural output is proxied by gross agricultural value added (GAVA), while the Digital Inequality Index serves as the main explanatory variable:

$$GAVA_{it} = \alpha + \beta DII_{it} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

where X_{it} is a vector of control variables, including capital investment in agriculture, labor productivity, irrigated land area, and access to financial resources. The terms μ_i and λ_t capture unobserved region-specific and time-specific effects, respectively, thereby controlling for structural heterogeneity and macroeconomic shocks.

To account for potential nonlinearities in the relationship between digital inequality and agricultural performance, an extended specification incorporating a quadratic term is estimated:

$$GAVA_{it} = \alpha + \beta_1 DII_{it} + \beta_2 DII_{it}^2 + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

This specification allows for the identification of threshold effects, whereby the marginal impact of digital inequality on output may vary depending on its level, reflecting the presence of nonlinear dynamics and potential diminishing or increasing returns.

In addition, the study introduces a framework for estimating the economic cost of digital inequality. This cost is defined as the difference between observed agricultural output and potential output under a counterfactual scenario of reduced digital inequality:

$$Loss_{it} = GAVA_{it}^* - GAVA_{it}$$

where $GAVA_{it}^*$ denotes the predicted level of output under a scenario in which digital inequality is minimized. This approach enables the quantification of unrealized productivity gains attributable to digital disparities and provides an economically interpretable measure of inefficiency.

Estimation is conducted using panel regression techniques, including pooled ordinary least squares (OLS), fixed effects (FE), and random effects (RE) models. The choice between FE and RE specifications is determined using the Hausman test, ensuring the consistency and efficiency of parameter estimates. To address potential econometric issues, robust standard errors are employed to correct for heteroskedasticity and serial correlation.

Model validation is performed using a set of diagnostic tests. Multicollinearity is assessed using variance inflation factors (VIF), heteroskedasticity is tested using the Breusch–Pagan test, and autocorrelation is evaluated using the Durbin–Watson statistic. These procedures ensure the statistical reliability and robustness of the estimated models.

Finally, a scenario analysis is conducted to evaluate the potential economic benefits of reducing digital inequality. Alternative scenarios are constructed by simulating improvements in the Digital Inequality Index, reflecting enhanced

access to digital infrastructure, technologies, and services. The corresponding changes in agricultural output are estimated using the model coefficients, enabling an assessment of potential gains from policy interventions aimed at reducing digital disparities.

Despite its analytical rigor, the proposed methodology has several limitations. First, the availability of detailed regional data on digital technology adoption remains constrained, necessitating the use of proxy indicators. Second, the aggregated nature of the dataset may obscure micro-level heterogeneity among individual farms and producers. Nevertheless, the adopted approach provides a robust and scalable framework for quantifying digital inequality and evaluating its economic consequences in the agricultural sector.

Results. The empirical analysis of digital inequality in agriculture across the southern regions of Kazakhstan demonstrates that, despite the overall progress in digital infrastructure development, significant spatial and structural disparities persist, exerting a measurable impact on agricultural productivity and economic performance. Over the period 2015–2025, all regions under consideration—Almaty, Zhambyl, Turkestan, and Kyzylorda—experienced a steady increase in key digitalization indicators, particularly in terms of internet penetration and access to communication technologies. However, the pace and depth of this transformation have been uneven, resulting in differentiated levels of digital readiness.

Table 1 — Digitalization indicators in southern regions of Kazakhstan (2015–2025)

Region	Internet (%) 2015	Internet (%) 2025	ICT use in agriculture (%)	Digital services access (%)
Almaty	62	91	48	55
Zhambyl	54	82	36	41
Turkestan	49	78	31	37
Kyzylorda	52	80	34	39

As shown in Table 1, Almaty region exhibits the highest level of digital development, combining both advanced infrastructure and relatively high adoption of digital technologies in agriculture. In contrast, Turkestan and Kyzylorda regions lag behind, particularly in terms of the practical use of ICT-based agricultural solutions. Importantly, the results reveal a persistent gap between access to digital infrastructure and its effective utilization. While internet penetration has increased substantially across all regions, the adoption of digital technologies in agricultural production remains limited, indicating that digital inequality is driven not only by infrastructural constraints but also by differences in human capital, technological capabilities, and institutional support mechanisms.

To provide a more systematic assessment of these disparities, the Digital Inequality Index (DII) was constructed, capturing multiple dimensions of digital development, including infrastructure, usage, and economic integration. The estimated values of the index reveal a clear divergence in regional trajectories.

Table 2 — Digital Inequality Index (DII) by region

Region	DII (2015)	DII (2025)	Change
Almaty	0.62	0.85	+0.23
Zhambyl	0.54	0.73	+0.19
Turkestan	0.49	0.69	+0.20
Kyzylorda	0.51	0.71	+0.20

Although all regions demonstrate positive dynamics, the inter-regional gap remains substantial. Almaty region consistently maintains a leading position, while other regions show slower progress. The coefficient of variation ($CV \approx 0.12$ in 2025) confirms the persistence of moderate but stable inequality, suggesting that digital convergence across regions is incomplete. This pattern indicates that structural constraints continue to limit the diffusion of digital technologies, particularly in less developed regions.

The econometric analysis further substantiates the critical role of digital inequality in shaping agricultural economic outcomes. The baseline panel regression results indicate a strong and statistically significant relationship between the Digital Inequality Index and agricultural output.

Table 3 — Baseline panel regression results (dependent variable: GAVA)

Variable	Coefficient	Std. Error	t-stat	p-value
DII	0.58	0.14	4.12	0.001
Investment	0.27	0.10	2.70	0.012
Labor productivity	0.34	0.11	3.09	0.006
Irrigated land	0.19	0.08	2.38	0.025
Constant	-1.05	0.59	-1.78	0.084

Model statistics	Value
R ²	0.81
Adjusted R ²	0.77
F-statistic	14.3
Prob(F)	0.000

The estimated coefficient for DII ($\beta = 0.58$, $p < 0.01$) indicates that improvements in digital inclusion are associated with a significant increase in agricultural output. In practical terms, a 0.1 increase in the index corresponds to an approximate 5.8% rise in gross agricultural value added, underscoring the economic importance of digital factors. At the same time, traditional determinants such as labor productivity and capital investment remain significant, suggesting that digitalization complements rather than substitutes conventional growth drivers. The high explanatory power of the model ($R^2 = 0.81$) confirms the robustness of the estimated relationships.

To further explore the nature of this relationship, a nonlinear specification was estimated, incorporating a quadratic term for digital inequality.

Table 4 — Nonlinear model results

Variable	Coefficient	Std. Error	t-stat	p-value
DII	0.92	0.28	3.29	0.004
DII ²	-0.41	0.17	-2.41	0.022

The results provide clear evidence of diminishing returns to digitalization, as indicated by the negative coefficient of the squared term. This implies that the marginal impact of digital development is strongest at intermediate levels and decreases as digital saturation is approached. Such nonlinear dynamics are consistent with the presence of threshold effects and network externalities, suggesting that the benefits of digitalization are not uniform across different stages of development.

A particularly important finding of the study is the estimation of the economic cost associated with digital inequality. By comparing actual output levels with a counterfactual scenario of reduced disparities, it is possible to quantify unrealized productivity gains.

Table 5 — Estimated economic losses due to digital inequality

Region	Actual GAVA (bln KZT)	Potential GAVA (bln KZT)	Loss (%)
Almaty	820	890	8.5
Zhambyl	510	610	19.6
Turkestan	730	880	20.5
Kyzylorda	460	550	19.3

The results indicate that regions with lower levels of digital development experience significantly higher economic losses. In Turkestan and Zhambyl regions, unrealized output exceeds 19–20%, highlighting the substantial economic cost of digital inequality. Even in the most advanced region, Almaty, the estimated losses remain non-negligible, suggesting that further improvements in digital integration could still yield additional gains.

To assess the potential impact of policy interventions, a scenario analysis was conducted based on simulated improvements in the Digital Inequality Index.

Table 6 — Scenario analysis of digital inequality reduction

Scenario	DII increase	Expected GAVA growth
Moderate	+10%	+6.2%
Accelerated	+20%	+11.8%
Digital parity	Equalization	+15.4%

The scenario results demonstrate that reducing digital inequality can generate substantial economic benefits, particularly in lagging regions. The estimated gains are nonlinear, with more pronounced effects observed under coordinated and large-scale improvements. The digital parity scenario, which assumes convergence in digital development across regions, yields the highest increase in output (+15.4%), emphasizing the importance of reducing structural disparities rather than focusing solely on incremental improvements.

Taken together, the empirical findings provide strong evidence that digital inequality constitutes a significant constraint on agricultural development in southern Kazakhstan. While progress in digital infrastructure has been substantial, disparities in access, adoption, and effective utilization continue to limit productivity gains. Addressing these challenges is therefore essential for unlocking the full economic potential of digitalization and ensuring inclusive and sustainable growth in the agricultural sector.

Discussion. The empirical findings of this study provide robust evidence that digital inequality constitutes a critical structural constraint on agricultural development in the southern regions of Kazakhstan. The results not only confirm the positive role of digitalization in enhancing agricultural productivity but also reveal that uneven access to and utilization of digital technologies significantly limit the realization of these benefits. In this regard, the study contributes to the growing body of literature emphasizing that digital transformation is inherently uneven and may reinforce existing economic disparities if not accompanied by inclusive policies.

The positive and statistically significant relationship between the Digital Inequality Index and agricultural output is consistent with prior empirical research highlighting the productivity-enhancing effects of digital technologies (FAO, 2022; Goldfarb & Tucker, 2019). Digital tools such as precision agriculture, remote sensing, and digital advisory systems reduce information asymmetries, optimize input use, and improve decision-making processes. In the context of Kazakhstan's agriculture, where production is highly sensitive to climatic variability and resource constraints, these technologies play a particularly important role in increasing efficiency and resilience. The magnitude of the estimated effect—where a 0.1 increase in digital inclusion corresponds to a 5.8% rise in output—underscores the economic significance of digitalization as a driver of sectoral growth.

At the same time, the results highlight that the benefits of digitalization are not distributed uniformly. The persistence of regional disparities, as reflected in the Digital Inequality Index and its dispersion, aligns with the concept of the “second-level digital divide,” which emphasizes differences in usage and outcomes rather than mere access (van Dijk, 2020). Even in regions where digital infrastructure has improved, such as Zhambyl and Kyzylorda, the relatively low levels of ICT adoption in agriculture indicate that access alone is insufficient to ensure effective digital transformation. This finding is consistent with the OECD (2020) and ITU (2023), which stress the importance of complementary factors such as digital skills, institutional capacity, and access to finance.

The presence of nonlinear effects, as evidenced by the quadratic specification of the model, provides further insight into the dynamics of digital transformation. The identified diminishing returns suggest that the impact of digitalization is strongest at intermediate stages of development, while marginal gains decrease as digital maturity increases. This pattern supports the theoretical framework of threshold effects and network externalities (Czernich et al., 2011), implying that regions

at early stages of digital development may require substantial initial investments before experiencing significant economic returns. Conversely, more advanced regions may face decreasing marginal benefits, highlighting the need for more sophisticated and innovation-driven digital strategies.

One of the most important contributions of the study is the quantification of the economic cost of digital inequality. The findings indicate that regions with lower levels of digital development experience substantial unrealized output, exceeding 19–20% in Turkestan and Zhambyl regions. This result provides empirical support for the argument that digital inequality is not merely a technological or social issue but a significant economic inefficiency. Similar conclusions have been drawn in the broader literature on digitalization, where unequal access to digital technologies has been shown to constrain productivity growth and exacerbate regional disparities (World Bank, 2021).

The scenario analysis further reinforces these conclusions by demonstrating that reducing digital inequality can generate substantial economic gains. The estimated increase in agricultural output under the digital parity scenario (15.4%) highlights the potential benefits of coordinated and inclusive digital policies. Importantly, the nonlinear nature of these gains suggests that policy interventions should not be limited to incremental improvements but should aim at systemic changes that address multiple dimensions of digital inequality simultaneously.

The findings also provide important insights into the structural nature of digital inequality in Kazakhstan's agricultural sector. The observed gap between infrastructure availability and actual technology use indicates that digital transformation is constrained by factors beyond physical connectivity. These include limited digital literacy among farmers, insufficient access to digital financial services, weak integration of digital tools into value chains, and institutional barriers to technology adoption. This observation is consistent with the broader literature emphasizing that digitalization is a socio-technical process requiring alignment between technological, institutional, and human capital dimensions (Acemoglu et al., 2005).

From a policy perspective, the results suggest that addressing digital inequality requires a comprehensive and multi-level approach. First, investments in digital infrastructure must be complemented by programs aimed at enhancing digital skills and competencies among agricultural producers. Second, improving access to digital financial services and platforms can facilitate the adoption of technologies and integration into modern value chains. Third, institutional reforms are needed to create an enabling environment for digital innovation, including regulatory frameworks, extension services, and public-private partnerships.

In addition, the regional heterogeneity identified in the study implies that policy interventions should be spatially differentiated. Lagging regions such as Turkestan and Kyzylorda require targeted support to overcome structural barriers, while more advanced regions such as Almaty may benefit from policies focused on innovation and technological upgrading. Such a differentiated approach is essential for

promoting balanced regional development and avoiding the deepening of existing inequalities.

Despite the robustness of the results, several limitations should be acknowledged. The use of aggregated regional data may mask micro-level heterogeneity among individual farms, and the reliance on proxy indicators for digitalization may not fully capture the complexity of digital adoption. Future research could address these limitations by incorporating farm-level data and exploring the role of specific digital technologies in greater detail.

Overall, the findings of this study contribute to the understanding of digital inequality as a key determinant of agricultural performance in transition economies. By demonstrating both the productivity-enhancing effects of digitalization and the economic costs of its uneven distribution, the study provides a strong empirical foundation for the design of policies aimed at promoting inclusive and sustainable digital transformation in agriculture.

Conclusion. This study provides a comprehensive empirical assessment of digital inequality in agriculture and its economic implications in the southern regions of Kazakhstan. The results demonstrate that digitalization constitutes a significant determinant of agricultural productivity, while digital inequality acts as a structural constraint that limits the realization of its full economic potential.

The analysis confirms the existence of substantial regional disparities in access to and use of digital technologies. Although digital infrastructure has expanded considerably over the past decade, its distribution and utilization remain uneven across regions. This imbalance leads to differentiated economic outcomes, with more digitally advanced regions achieving higher levels of agricultural output and efficiency, while less developed regions experience lower productivity and reduced growth potential.

The econometric results reveal a statistically significant relationship between digital inclusion and agricultural performance, highlighting the critical role of digital technologies in enhancing productivity. At the same time, the identified nonlinear effects indicate that the benefits of digitalization depend on reaching a certain threshold of development, beyond which productivity gains become more pronounced. This finding underscores the importance of cumulative and network effects in the digital transformation of agriculture.

A key contribution of the study lies in the quantification of the economic cost of digital inequality. The results show that regions with lower levels of digital development incur substantial losses in terms of unrealized output and missed productivity gains. These findings suggest that digital inequality is not only a technological or social issue but also a major economic inefficiency that reduces the overall performance of the agricultural sector.

The study also highlights the importance of structural and institutional factors in shaping the effectiveness of digitalization. The limited integration of digital technologies into production processes, combined with disparities in human capital and institutional capacity, constrains the economic impact of digital transformation.

This indicates that expanding infrastructure alone is insufficient; it must be complemented by policies that promote the effective use of digital technologies.

From a policy perspective, the findings suggest the need for a strategic shift from infrastructure-oriented digital policies toward a more integrated approach to digital transformation. Such an approach should prioritize the development of digital skills, support for the adoption of digital technologies in agriculture, strengthening of institutional frameworks, and promotion of innovation ecosystems. Particular attention should be given to lagging regions, where targeted interventions can generate the highest marginal returns in terms of productivity and growth.

In a broader context, the results position Kazakhstan at an intermediate stage of digital transformation, where the foundations of digital infrastructure are largely in place, but the transition toward full economic integration of digital technologies remains incomplete. Bridging this gap requires coordinated efforts to align technological development with institutional reforms and human capital development.

In conclusion, the study demonstrates that reducing digital inequality is a critical prerequisite for achieving inclusive and sustainable agricultural growth. The effectiveness of digitalization depends not only on its scale but also on the depth of its integration into economic and institutional systems. Addressing digital disparities can unlock significant productivity gains and contribute to the long-term competitiveness of the agricultural sector in Kazakhstan.

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