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IDENTIFYING DIGITALIZATION'S IMPACT ON HOW ENERGY SECTOR COMPANIES PERFORM ENVIRONMENTALLY AND FINANCIALLY

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The object of the study is energy sector companies in the Republic of Kazakhstan involved in the extraction, transportation, generation, transmission, and distribution of energy resources. The problem addressed is the insufficient understanding of the mechanism through which digitalization affects financial performance, since it remains unclear whether this effect is direct or transmitted through environmental performance indicators.

The empirical basis of the study is a balanced quarterly panel dataset for 2015–2025, comprising 220 observations across five companies. Fixed-effects models, a dynamic lagged model, panel vector autoregressive models, and impulse response functions were used in the study.

The results show that digitalization has a statistically significant negative effect on carbon intensity in the fixed-effects model ($\beta = -0.2828$; $p < 0.01$), whereas its direct effect on return on assets is not statistically confirmed ($\beta = -0.0035$; $p > 0.10$). Carbon intensity has a significant negative effect on financial performance in both the static fixed-effects model ($\beta = -0.0118$; $p < 0.01$) and the dynamic lagged model ($\beta = -0.00213$; $p < 0.05$). These findings provide indirect empirical support for a possible environmental transmission channel, in which digitalization is associated with a lower environmental burden that may subsequently contribute to financial performance.

The study uses quarterly corporate data, a text-based digitalization indicator, and carbon intensity as a measure of environmental performance, allowing an indirect assessment of a possible environmental transmission mechanism.

The results can be used by energy companies, regulators, and investors when developing digital transformation and decarbonization strategies and making ESG-related investment decisions

Keywords: carbon intensity, digitalization, fixed effects, energy logistics, the Republic of Kazakhstan

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1. Introduction

The digitalization study's relevance for the energy sector is determined by a simultaneous impact of two strategic challenges: the need to reduce environmental impacts and ensure financial sustainability. Energy companies operate in a highly capital-intensive and resource-dependent environment where production efficiency, emission control, asset utilization, and

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investment decisions are interrelated very closely. In such conditions, digitalization is viewed not only as a process of technological modernization but also as a potential driver of improved environmental and financial performance.

Modern energy companies utilize digital technologies to improve monitoring, data processing, resource management, infrastructure control, and management decision-making. This reduces operational losses [1], increases production process transparency [2], and improves environmental accounting [3]. Therefore, scientific research on this topic is essential as digitalization's role extends beyond automation and is becoming an element of decarbonization, operational efficiency, and long-term competitiveness.

At the same time, the relationship between digitalization, environmental performance, and financial indicators remains insufficiently defined. Digitalization has been shown to be relevant for company value, especially when combined with corporate sustainability practices [4]. Big data, sustainability, and digitalization are also associated with company performance through improved information processing and strategic decision-making [5]. In addition, the relationship between digitalization, sustainability, and organizational performance has been conceptualized as multidimensional, indicating that the mechanisms linking these areas require further clarification [6]. However, such effects are not universal and can be both indirect and dynamic. In capital-intensive industries [7] that include energy, digitalization effects can manifest themselves with a time lag and through intermediate mechanisms primarily related to environmental performance.

In the energy sector, the relevance of this topic is reinforced by the need to combine digital transformation with decarbonization and financial sustainability. Digital technologies can improve monitoring, resource allocation, production control, environmental accounting, and managerial decision-making. At the same time, the effects of digitalization may differ depending on industry characteristics, capital intensity, regulatory pressure, and the structure of corporate investment. Therefore, the relationship between digitalization, environmental performance, and financial performance cannot be considered universal or automatically positive.

For energy companies, this issue is especially important because environmental performance and financial performance are closely connected through production efficiency, emission intensity, resource use, investment costs, and exposure to external market conditions. In this context, digitalization may act not only as a technological modernization process but also as a factor associated with environmental and economic outcomes. Therefore, studies that are devoted to the relationship between digitalization, environmental performance, and financial performance in energy sector companies are of scientific relevance.

2. Literature review and problem statement

The literature on digitalization, environmental performance, and financial performance covers three main areas: corporate financial effects, environmental outcomes, and energy-sector applications. This section systematizes these areas and identifies unresolved issues related to company-level evidence and transmission mechanisms.

In paper [8], the authors present research results showing that digital transformation contributes to the simultaneous improvement of companies' financial performance and sustainability, thus creating a synergistic effect. In [9], it is shown that digitalization strengthens the relationship between sustainable practices and economic results, which increases business model efficiency. However, these studies do not fully disclose whether digitalization's impact on financial performance is direct or whether it is transmitted through environmental performance indicators.

In paper [10], the authors show that digitalization and servitization have a positive impact on financial performance through improved operational efficiency. In [11], the authors demonstrate the importance of energy intensity and the Republic of Kazakhstan's resource specificity for assessing efficiency in a resource-export economy. In [12], it is shown that investments in production digitalization contribute to improved financial performance of companies. In paper [13], the authors confirm that corporate finance digitalization has a positive impact on company profitability and sustainability.

That aside, [14] notes insufficient study of digitalization's long-term and dynamic consequences on financial performance. Furthermore, digitalization's effect depends on company size, region, industry, institutional environment, and digital investment type. Therefore, the question remains unresolved as to whether digitalization's financial effect is direct and universal or manifests itself through specific organizational and environmental conditions.

Another group of studies links digitalization with environmental performance. In paper [15], the authors show that digitalization contributes to improved environmental performance through increased resource efficiency and technological change. In paper [16], the authors emphasize the role of digital technologies in expanding environmental accounting tools and multidimensional assessment of environmental performance. In paper [17], it is shown that digital transformation affects environmental performance through technological and organizational effects.

Meanwhile, a number of studies emphasize digitalization's dual nature. In paper [18], the authors note that digital technologies can simultaneously improve environmental performance and place additional strain on resources. In paper [19], it is shown that digitalization's effect depends on the combination of technological and environmental practices. In [20], the authors found that digitalization can contribute to an increase in the carbon footprint due to increased energy consumption. In paper [21], similar conclusions are offered, highlighting digitalization's ambiguous impact on environmental sustainability.

Therefore, digitalization is not a "green" factor by default, and its environmental impact requires empirical verification at the level of specific measurable indicators.

Studies that simultaneously examine digitalization, sustainability, and financial performance also provide controversial results. In paper [22], the authors argue that ESG practices are positively associated with company performance, but digitalization's independent effect is not always confirmed. In paper [23], the authors reveal a paradox of supply chain digitalization: digital investments improve non-financial indicators but can also reduce financial performance due to increased risks and resource redundancy. In [24], the authors confirm that the impact of digital business strategy on financial performance depends on sustainability strategy. In paper [25], it is shown that digitalization has a positive impact on firm value, profitability, and green initiatives, but this effect may be short-term and nonlinear. These results indicate that the relationship between digitalization and financial performance is not always direct but may be mediated by environmental and organizational channels.

This issue is crucial for the energy sector. In paper [26], the authors show that ESG integration is positively related to the financial performance of energy and utility companies, and that digitalization can strengthen this relationship. In paper [27], the authors confirm the relationship between digitalization and corporate responsibility practices in Polish energy companies. In paper [28], it is shown that digitalization and green finance have a positive impact on the green transformation of a mineral energy company. In paper [29], the authors reveal digitalization micro-mechanisms through energy conservation, emission reduction, and operational optimization. In paper [30], the authors reveal an ambiguous relationship between decarbonization and profitability of energy companies. However, many studies use aggregated ESG indicators, survey data, annual observations, macro-level assessments, or case studies, which complicates the assessment of digitalization's impact on specific corporate indicators, including carbon intensity and return on assets.

In paper [31], the authors present results closest to the present study, demonstrating that digital transformation of renewable energy companies has a positive impact on financial performance. This effect is also confirmed in paper [32], where it is linked to improved operational efficiency and cost reduction. Furthermore, in paper [33], green technological innovation is identified as the key mechanism for transmitting this impact. However, these studies rely on innovation and operational changes as mediators rather than on actual environmental performance measured by carbon intensity. Moreover, the analysis is based primarily on annual data, which limits the ability to identify short-term and lagged effects.

Macro-level studies also confirm digitalization's significance for environmental and energy performance. In paper [34], the authors demonstrate digitalization's impact on energy risks and sustainability. In paper [35], the link between digital technologies, energy consumption, and economic growth is identified. In paper [36], the authors establish digitalization's role in improving environmental performance through energy efficiency and financial development. However, these studies are conducted at the country and regional levels. Their findings do not directly explain the behavior of individual companies, since decisions regarding digital transformation, carbon intensity reduction, and financial efficiency are made at the corporate strategy level.

Accordingly, a literature review identifies several localized unresolved issues. First, a significant portion of the study views digitalization as a general factor in industry, regional, or national transformation while direct assessments of its impact on specific company indicators are scarce. Second, studies of digitalization and financial performance yield mixed results as the effect varies by industry, company size, region, and type of digital investment. Third, studies of digitalization and environmental performance often fail to consider financial indicators as a downstream mechanism. Fourth, oftentimes, energy sector studies use aggregated ESG indicators while the specific environmental channel associated with carbon intensity is disclosed insufficiently. Fifth, a significant portion of the literature is based on annual data, static models, surveys, or case studies, thus limiting the analysis of dynamic and lagged effects.

These questions remain unresolved for both objective and methodological reasons. The objective reason stems from the limited availability of comparable corporate data on digitalization, emissions, and financial performance, particularly at the quarterly level. The methodological reason lies in the differences in how digitalization is measured: through investments, indices, text analysis, survey assessments, or binary indicators of technology adoption. Furthermore, a multitude of studies describe digitalization as a condition or development direction but fail to assess its impact on specific environmental and financial indicators in a unified model. As a result, testing of the environmental transmission channel of digitalization's impact appears insufficient.

Overall, previous studies show that digitalization may affect environmental performance, financial performance, and corporate sustainability. However, the existing evidence remains fragmented. Macro-level studies usually rely on national ICT indicators, sectoral studies often use aggregated ESG or industry-level measures, while corporate-level studies apply investment, survey, textual, or technology-adoption indicators. As a result, less attention has been paid to company-level evidence based on measurable environmental and financial indicators, especially in the energy sector.

Therefore, a general unresolved problem is the lack of empirical evidence on whether digitalization has a direct impact on the financial performance of energy sector companies or whether its effect is realized through changes in environmental performance. Especially understudied is digitalization's dynamic mechanism of reducing carbon intensity while changes in environmental performance are subsequently reflected in financial performance. This justifies the need for the study aimed at determining digitalization's impact on environmental and financial performance of energy sector companies and assessing a possible environmental transmission channel.

3. The aim and objectives of the study

The aim of the study is to determine digitalization's impact on environmental performance and financial performance of energy sector companies. This will help establish whether digitalization has a direct impact on companies' financial performance or whether its effect is realized primarily through a reduction in carbon intensity.

To achieve this aim, the following objectives were accomplished:

– to generate and verify quarterly panel data at the company level, as well as to assess descriptive characteristics, correlations, and stationarity of key variables;

– to evaluate fixed-effects models of environmental and financial performance using digitalization, carbon intensity, and control variables;

– to identify the nature of the relationship between environmental performance and companies' financial performance measured by return on assets;

– to assess dynamic effects and indirect empirical evidence for a possible transmission mechanism between digitalization, environmental performance, and financial performance using lagged models, panel vector autoregressive models, and impulse response functions.

4. Materials and methods

4. 1. The object and hypothesis of the study

The object of the study is energy sector companies in the Republic of Kazakhstan involved in the extraction, transportation, generation, transmission, and distribution of energy resources. The main hypothesis of the study is that digitalization affects the environmental and financial performance of energy sector companies, while its financial effect may be realized not only directly but also through changes in environmental performance.

The sample includes KazMunayGas, KazTransOil, QazaqGaz, KEGOC, and Samruk-Energy, all part of the Samruk-Kazyna investment holding. These companies represent energy production, transportation, and energy production, providing a unified industry context for the analysis.

This selection was based on the availability of quarterly financial and non-financial reporting required for constructing a balanced panel, as well as a high data disclosure and comparability levels.

Fig. 1 presents the conceptual framework of the study.

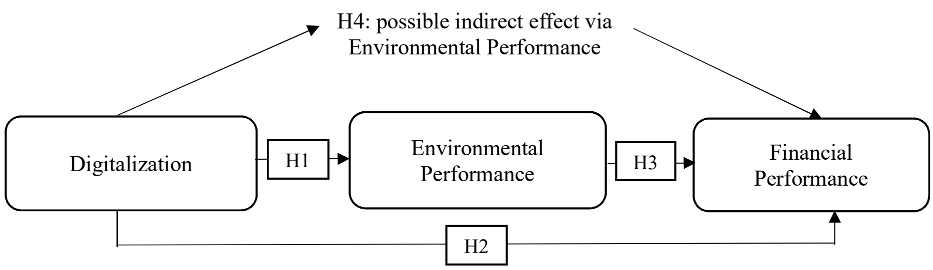

Fig. 1. Conceptual model of digitalization's impact on environmental and financial performance with a possible indirect environmental channel

The model hypothesizes digitalization's both direct and indirect effects on financial performance. The environmental channel is considered as a possible mechanism: digitalization may reduce carbon intensity, which may be indirectly associated with financial performance.

In accordance with this research logic, the following hypotheses were formulated:

H1. Increased digitalization is linked to improved environmental performance of companies, which is manifested in a reduction in CO_2 emission intensity.

H2. Increased digitalization directly impacts financial performance of companies measured by return on assets.

H3. Environmental performance of companies is associated with financial performance, with an increase in CO_2 emission intensity negatively impacting profitability.

H4. Digitalization's impact on company financial performance may receive indirect empirical support through the environmental channel.

H5. Digitalization's impact on environmental and financial performance is dynamic and manifests itself with a time lag.

Methodological assumptions include treating companies as comparable elements of a single energy sector despite their differences in specialization. Digitalization is measured using a text proxy, carbon intensity is used as an indicator of environmental performance, and financial performance is assessed using ROA.

The analysis is limited to the largest companies with available comparable financial statements. Environmental performance is represented by an aggregated indicator, digitalization is represented by an integrated characteristic without differentiation by technology, and financial performance assessment does not consider market indicators. This approach ensures data comparability and appropriateness of applying panel and dynamic analysis methods.

4. 2. Panel dataset formation and structure

A balanced panel dataset at the company and quarter levels serves as the empirical basis of the study. The observation period covers a period between 2015 and 2025 with quarterly figures. For each company, 44 observations were generated for a total sample size of 220. The structure corresponds to a balanced panel and enables applying panel and dynamic analysis methods.

Data took several stages to prepare. The initial dataset was loaded into the R environment, followed by verification and standardization of variable names and data types. Then a panel structure identified by company and quarter was created. Missing data, duplicates, and outliers were checked, and variability of variables was assessed to eliminate constant and quasi-constant indicators.

For the final stage, the required data transformations were performed. This included taking the logarithm of individual variables and converting the indicators into a form suitable for econometric analysis. The final dataset was sorted chronologically and converted to a panel format for further modeling.

The environmental performance indicator is primarily disclosed annually. In the quarterly panel, the same annual carbon intensity value was assigned to all four quarters of the corresponding year for each company. Therefore, this indicator is used to preserve the quarterly panel structure and is not interpreted as actual intra-annual variation in carbon intensity.

4. 3. Research variables and their calculation

Table 1 systematizes the model's key indicators, including the explanatory digitalization variable, dependent variables of environmental and financial performance, and control factors.

Table 1

Defining and Measuring Variables

Indicator	Designation	Calculation	Description
Digitalization	Digitalization	Number of digital dictionary term occurrences divided by the total number of words in the cleaned financial statements and multiplied by 1000	A text proxy for a company's digital activity: it reflects digital disclosure intensity in corporate reporting
Environmental performance	CO_2_Intensity	CO_2 emissions to revenue ratio	Carbon intensity: a decrease in the value reflects improved environmental performance
Financial performance	ROA	Net profit to total assets ratio	Asset utilization efficiency indicator
Leverage	Leverage	Long-term and short-term debt to total assets ratio	Characterizes the company's debt load
Oil price	Brent	Average market price of Brent crude oil for the period	A control variable reflecting external price conditions
Exchange rate	FX_Avg	Average KZT-USD exchange rate for the period	A control variable reflecting foreign exchange conditions

The digitalization indicator is based on a text analysis of annual reports, sustainability reports, and official corporate publications from KazMunayGas, KazTransOil, QazaqGaz, KEGOC, and Samruk-Energy for 2015–2025.

To ensure comparability, all documents were converted to a standard text format. Tables, numerical values, duplicate fragments, navigation elements, and service characters were removed. The text was then unified to a single case and the spelling of terms was standardized.

The digitalization indicator was calculated using a fixed dictionary of digital terms, such as digital, digitalization, digital transformation, AI, artificial intelligence, big data, data analytics, automation, ERP, SAP, cloud, IoT, blockchain, platform, IT, and system. The dictionary was consistent across all companies and years of observation, ensuring comparability of the results. The frequency of digital term occurrences was checked by company and year before normalization, which allowed to identify differences in digital disclosure intensity across firms.

The number of digital references was normalized by the total volume of the cleaned text. This means the indicator reflects relative intensity of digital topic disclosure in the reporting. For the quarterly panel, the annual indicator value was assigned to all four quarters of the corresponding year using a uniform rule for all companies.

Environmental performance is represented by the carbon intensity indicator that characterizes the level of emissions relative to economic activity. A reduction in this indicator is interpreted as an improvement in environmental performance and serves as a key indicator of the possible environmental channel.

Financial performance is measured by ROA (Return on Assets) that reflects the efficiency of a company's resource use.

The model also uses control variables. Financial leverage accounts for companies' debt burden while macroeconomic indicators (Brent crude oil price and exchange rate) reflect energy sector's external conditions.

In order to improve the econometric analysis accuracy, it is possible to use variable transformations. For the digitalization and carbon intensity indicators, it is possible to take logarithms with the addition of a small positive constant to account for zero values and reduce distribution asymmetry.

4. 4. Econometric strategy

The econometric analysis took several sequential stages aimed at testing static and dynamic relationships between variables.

The first stage involves a preliminary data analysis, including descriptive statistics, a correlation matrix, and panel data stationarity tests. The IPS (Im-Pesaran-Shin) test that considers the panel structure's heterogeneity is used to test stationarity. Then additional diagnostic checks were performed: multicollinearity was assessed using a VIF (Variance Inflation Factor) with values below critical thresholds while heteroscedasticity was accounted for by applying robust standard errors (HC1). This stage ensures appropriate selection of model specifications and justification of dynamic component inclusion.

Despite the identified nonstationarity of individual variables, their use in the levels is justified by the limited time dimension of the panel and the study's focus on assessing structural relationships between indicators. This approach is consistent with panel research practices focused on identifying economic dependencies rather than modeling long-term equilibrium relationships.

For the second stage, FE (Fixed Effects) models are estimated. This specification was selected to account for unmeasured, constant company characteristics, including size, industry specialization, and business model features. The preference for fixed effects models is confirmed by a Hausman test that confirms their superiority over random effects.

The basic model for digitalization's impact on environmental performance is as follows

$$\ln\left(\mathrm{CO}_{2_{Intensityit}}\right) = \alpha_i + \beta_1 \ln\left(Digitalization_{it}\right) + \beta_2 Leverage_{it} + \beta_3 Brent_t + \beta_4 FX_{Avgt} + \varepsilon_{it}. \quad (1)$$

Assessing the relationship between digitalization, environmental and financial performance involves using the following specification

$$ROA_{it} = \alpha_i + \beta_1 \ln\left(Digitalization_{it}\right) + \beta_2 \ln\left(\mathrm{CO}_{2_{Intensityit}}\right) + \beta_3 Leverage_{it} + \beta_4 Brent_t + \beta_5 FX_{Avgt} + \varepsilon_{it}. \quad (2)$$

These models allow to assess both digitalization's direct impact on financial performance and environmental performance's impact, thus forming the basis for assessing indirect empirical support for the possible environmental channel.

For the third stage, it is possible to apply a dynamic model with lags that takes into account the indicators' temporal inertia and the impact's delayed nature

$$ROA_{it} = \alpha_i + \rho ROA_{i,t-1} + \beta_1 \ln\left(Digitalization_{i,t-1}\right) + \beta_2 \ln\left(\mathrm{CO}_{2_{Intensityi,t-1}}\right) + \beta_3 Leverage_{i,t-1}. \quad (3)$$

Including lagged variables allows to identify dynamic effects and test the hypothesis on the temporal nature of digitalization's and environmental performance's impact.

For the fourth stage, it is possible to use PVAR (Panel Vector Autoregression) that allows to analyze interdependence of variables over time without rigidly specifying a causal structure. The optimal lag length in the model was determined based on AIC and BIC information criteria, the final specification uses one lag.

The model includes three endogenous variables: digitalization, carbon intensity, and return on assets

$$Y_{it} = \alpha_i + A_1 Y_{i,t-1} + \mu_i + \varepsilon_{it}, \quad (4)$$

where Y_{it} – a vector of variables (*Digitalization*, $\mathrm{CO}_{2_{Intensity}}$, *ROA*), A_1 – a matrix of lagged coefficients, μ_i are individual effects, and ε_{it} is the error vector.

Based on PVAR, IRFs (Impulse Response Functions) are calculated to assess the response of environmental and financial performance to digitalization shocks, as well as the impact of changes in carbon intensity on financial performance.

Accordingly, the chosen econometric strategy provides a test of direct and dynamic relationships, as well as an indirect assessment of a possible environmental transmission channel, without implying a formal mediation test.

5. Results of assessing the digitalization's impact on companies' environmental and financial performance

5. 1. Data characteristics and preliminary analysis

The first stage of the empirical analysis seeks to test the initial panel data's structure and statistical properties, which included 220 quarterly observations across 44 quarters for five energy sector companies. The analysis included indicators of digitalization, environmental performance, financial performance, and control variables. Tables 2–4 present the main results of the preliminary analysis.

Table 2 shows that the data are characterized by significant between-firm and time-varying heterogeneity.

Table 2

Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Median	Max
ROA	220	0.0130	0.0151	−0.0526	0.0116	0.0659
Leverage	220	0.1903	0.1273	0.0000	0.2134	0.4638
Brent	220	66.4561	18.4096	29.1900	66.9100	113.9300
FX_{Avg}	220	395.9826	82.2830	184.5800	417.6900	536.5200
$CO_{2_{Intensity}}$	220	25.1148	50.9926	0.0004	1.0925	151.0000
Digitalization	220	0.0303	0.0602	0.0001	0.0032	0.2360

Table 2 shows that the average ROA (Return on Assets) is 0.0130 with a range of −0.0526 to 0.0659, reflecting variations in companies' financial performance across periods. Capital-intensive industries, including the energy sector, typically exhibit ROA in the range of 0.02–0.08. In this context, on average, the obtained values are below the typical industry level and tend towards the spectrum's lower end, thus indicating restrained financial performance and presence of negative return periods.

Financial leverage averages 0.1903, thus indicating moderate debt burden with some observations containing zero values.

Macroeconomic variables exhibit significant volatility. Over the study period, the Brent crude oil prices ranged from 29.19 to 113.93 USD per barrel while the exchange rate ranged from 184.58 to 536.52 tenge per dollar. These factors are included in the models as control variables reflecting external operating conditions of energy sector companies.

Carbon intensity is characterized by a highly skewed distribution (mean 25.11, median 1.09), effectively indicating the presence of emissions and significant right-handed skewness.

The digitalization indicator shows a pronounced uneven distribution (mean 0.0303, median 0.0032), thereby indicating differences in the level of digital activity among the analyzed companies.

The correlation analysis presented in Table 3 allows for a preliminary assessment of the direction of the variable relationships.

Table 3

Correlation Matrix

#	Variable	1	2	3	4	5	6
1	*Digitalization*	1.000	−0.198	−0.059	−0.633	0.106	0.194
2	$CO_{2_{Intensity}}$	−0.198	1.000	−0.343	0.512	−0.055	−0.107
3	*ROA*	−0.059	−0.343	1.000	−0.196	0.104	0.236
4	*Leverage*	−0.633	0.512	−0.196	1.000	−0.210	−0.304
5	*Brent*	0.106	−0.055	0.104	−0.210	1.000	0.497
6	FX_{Avg}	0.194	−0.107	0.236	−0.304	0.497	1.000

Table 3 data show the digitalization indicator's negative relation to carbon intensity (−0.198), which is consistent with hypothesis H1. The relationship between digitalization and return on assets is weak (−0.059), which does not preliminarily indicate a strong direct link between digitalization and financial performance. Furthermore, the negative correlation between digitalization and carbon intensity, as well as between carbon intensity and ROA, is tentatively consistent with the environmental channel's logic. A final test of H2–H4 is conducted subsequently in regression and dynamic models.

A positive relationship is observed between carbon intensity and financial leverage (0.512) while the highest absolute correlation is between digitalization and leverage (−0.633) without reaching critical multicollinearity values. Overall, the correlation matrix reveals no multicollinearity issues and confirms variable applicability in the regression analysis.

For the next step, unit root tests were performed on the panel data. Table 4 presents the results.

Table 4

Panel unit root test results (Im-Pesaran-Shin, IPS)

Variable	Test	Statistic	p-value	Conclusion
ROA	IPS	−7.8528	< 0.001	Stationary
Digitalization (log)	IPS	3.3646	0.9996	Non-stationary
$CO_{2_{Intensity}}$ (log)	IPS	0.2561	0.6011	Non-stationary

The IPS (Im-Pesaran-Shin) test results show that return on assets is stationary (statistic −7.8528; $p < 0.001$) while the logarithmic digitalization (3.3646; $p = 0.9996$) and carbon intensity (0.2561; $p = 0.6011$) indicators are non-stationary.

These estimates indicate a pronounced dynamic component in the digitalization and environmental performance indicators as opposed to financial performance, thereby justifying the use of dynamic specifications, including lagged models, panel vector autoregressive models, and impulse response functions.

The IPS test results highlight the need for cautious model interpretation in levels as the logarithmic digitalization and carbon intensity indicators are non-stationary. The following analysis is conducted in levels and considers the panel's limited temporal dimension and the study focus on assessing the structural relationships between digitalization, environmental and financial performance.

Additional diagnostic checks confirmed the appropriateness of the selected specifications. The Hausman test supported the use of fixed effects models. The VIF values were below critical thresholds, indicating no serious multicollinearity. Heteroscedasticity was addressed using HC1 robust standard errors. The PVAR lag length was selected based on AIC and BIC criteria, both supporting a one-lag specification. Sensitivity checks with alternative specifications did not change the direction of the main relationships.

5. 2. Fixed-effects estimates of environmental and financial performance models

Table 5 presents the fixed-effects model's results.

The digitalization indicator has a statistically significant negative impact on carbon intensity (β = -0.2828; $p < 0.001$), thereby indicating a decrease in emissions as companies increase their digital activity. This result supports hypothesis H1.

Control variables show mixed results. Financial leverage is positively related to carbon intensity and negatively related to *ROA*. Among the macroeconomic variables, *Brent* is not statistically significant while FX_{Avg} has a significant positive relationship with carbon intensity and a weakly significant positive relationship with ROA.

Table 5

Fixed effects estimates of environmental and financial performance models

Variables	(1) CO_2 (log)	(2) ROA
Digitalization (log)	−0.2828***	−0.0035
	(0.0534)	(0.0027)
$CO_{2_{Intensity}}$ (log)	–	−0.0118***
		(0.0037)
Leverage	0.9767**	−0.0522***
	(0.3260)	(0.0193)
Brent	0.0007	−0.00004
	(0.0011)	(0.00005)
FX_{Avg}	0.0011**	0.00003*
	(0.0004)	(0.00002)
Firm FE	Yes	Yes
Observations	220	220
R^2	0.284	0.165
Adj. R^2	0.257	0.129

*Note: *** – p < 0.01, ** – p < 0.05, * – p < 0.10.*

These results demonstrate that digitalization acts as a factor in improving environmental performance. Given the lack of a direct relationship with financial indicators (ROA Model 2), this effect forms the basis for an indirect mechanism for digitalization's impact on financial performance through the environmental channel.

5. 3. Environmental performance and financial performance

The fixed-effects model's results (Table 5) indicate a statistically significant negative impact carbon intensity has on return on assets ($\beta = -0.0118$; $p < 0.01$), which supports hypothesis H3. However, the digitalization indicator does not demonstrate a statistically significant impact on financial performance ($\beta = -0.0035$; $p > 0.10$), which does not support hypothesis H2.

Accordingly, the obtained estimates indicate the absence of digitalization's direct effect on financial performance despite the environmental performance's significant impact, thereby supporting an indirect mechanism.

Additional results from the dynamic specification (Table 6) confirm the identified relationships.

The lagged return on assets is positive and statistically significant ($\beta = 0.318$; $p < 0.001$), thereby indicating financial performance's persistence. Lagged carbon intensity has a negative effect on current return on assets ($\beta = -0.00213$; $p < 0.05$), thus confirming this effect's persistence over time and further supporting hypothesis H3.

At the same time, the lagged digitalization indicator is not statistically significant ($p > 0.10$), which is consistent with the static model's results and points out the absence of either a short-term or a lagged direct effect of digitalization on financial performance.

Taken together, these results are indicative of the digitalization's impact on financial performance being indirect but also realizable through changes in environmental performance. This provides empirical support for hypothesis H4 but fails to formally test the mediation effect.

Table 6

Dynamic lagged OLS model

Variables	Coefficient	Std. Error	p-value
ROA $(t-1)$	0.318***	0.0649	0.0000
$CO_{2_{Intensity}}$ $(t-1$, log)	−0.00213**	0.00082	0.0105
Digitalization $(t-1$, log)	0.00054	0.00061	0.3790
Leverage	0.00907	0.01276	0.4783
Constant	0.01337***	0.00322	0.0000
Observations	220		
R^2	0.181		
Adj. R^2	0.165		

*Note: *** – p < 0.01, ** – p < 0.05, * – p < 0.10.*

5. 4. Dynamic interrelations and the transmission mechanism

Table 7 presents results of the panel vector autoregression.

Results of the panel vector autoregression reveal a pronounced key variable inertia. The lagged digitalization value has a positive and statistically significant effect on its current level ($\beta = 0.9144$; $p < 0.01$), thereby indicating cumulative nature of digital processes. Similarly, carbon intensity demonstrates high stability over time ($\beta = 0.9321$; $p < 0.01$), thus reflecting slow dynamics of environmental performance changes.

The most significant result relates to carbon intensity's impact on financial performance. Lagged carbon intensity has a negative impact on return on assets ($\beta = -0.0089$; $p < 0.10$), which is consistent with hypothesis H3. However, digitalization lag does not have a statistically significant direct effect on return on assets, thereby further confirming the absence of digitalization's direct financial effect.

Overall, Table 7 results show that the direct dynamic "digitalization-financial performance" channel was not statistically confirmed while the relationship between carbon intensity and ROA persists. This strengthens the case for the environmental channel but cannot replace a formal mediation test.

Fig. 2–4 present impulse response function estimates.

Carbon intensity's response to the digitalization shock (Fig. 2) is negative across the entire forecast horizon. Initial periods show the largest decline, followed by the effect's stabilization and gradual fade. Meanwhile, intersection of the confidence intervals with zero points to the effect's limited statistical significance. Therefore, the result should be interpreted as directional confirmation of the environmental channel rather than as a strictly statistically robust effect.

Table 7

Panel vector autoregression (PVAR) results

Dependent variable	Lagged digitalization	Lagged CO_2	Lagged ROA	Key interpretation
Digitalization	0.9144***	−0.0062	1.2880	Strong inertia of digitalization
CO_2 Intensity	−0.0063	0.9321***	−0.9275*	Strong inertia of environmental performance, dependence on financial performance
ROA	0.0019	−0.0089*	0.1825**	Negative impact of carbon intensity on financial performance

*Note: *** – p < 0.01, ** – p < 0.05, * – p < 0.10.*

Financial performance's response to the digitalization shock (Fig. 3) is positive but also short-lived. Initial periods show an increase in return on assets post-shock, followed by the effect's gradual decline and approaching zero. Wide confidence intervals point to high uncertainty in the estimate and the absence of digitalization's consistent direct impact on financial performance.

At the same time, the response of return on assets to the carbon intensity shock (Fig. 4) is consistently negative. Increasing carbon intensity leads to a decrease in financial performance over the entire analysis horizon with the effect's gradual decline over time. Despite partial intersection of the confidence intervals with zero, the effect's direction persists, thereby confirming existence of a negative relationship between environmental and financial performance.

Collectively, results of the dynamic analysis imply the hypothesized environmental channel's directional consistency with limited statistical significance of individual impulse responses. The relationship between digitalization and financial performance may manifest itself through changes in environmental performance. However, this finding should be viewed as indirect empirical support for H4 rather than as formal confirmation of a mediator effect.

Table 8 presents summary results of the hypotheses tests. The obtained estimates disclose the existence of relationships between digitalization and environmental and financial performance. However, interpretation of the dynamic and mediated effects requires caution given the limited statistical robustness of individual IRF results.

Analysis results show digitalization's significant impact on environmental performance by reducing carbon intensity, although it does not have a statistically significant direct effect on financial performance. At the same time, deteriorating environmental performance leads to a decrease in asset profitability, which is confirmed in both static and dynamic models.

The dynamic analysis reveals an inertial structure in key variables and certain lagged relationships. However, caution is required when interpreting impulse response function results as confidence intervals partially cross zero. Therefore, H5 is considered confirmed partially: a dynamic structure is detected in lagged OLS and PVAR but the IRF effect robustness is limited. Taken together, results imply that the relationship between digitalization and financial performance may manifest itself primarily through environmental performance. Still, this finding should be viewed as indirect empirical support for the environmental channel rather than as formal confirmation of a mediator effect.

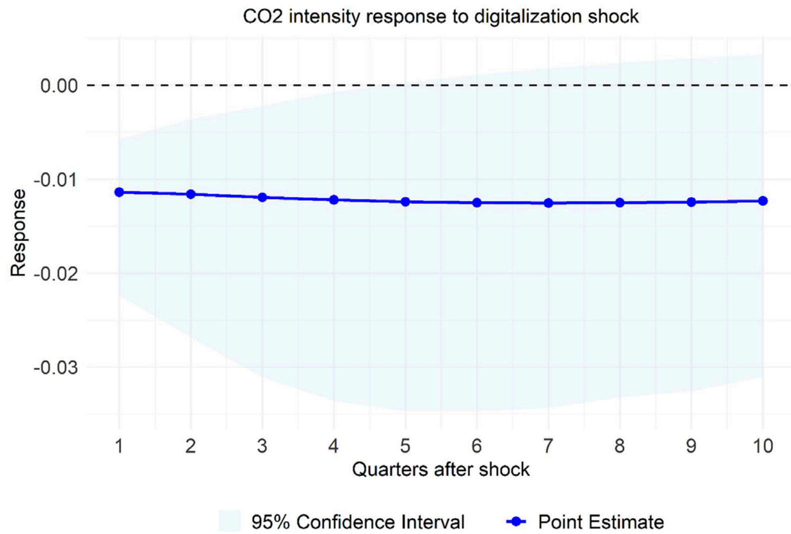

Fig. 2. Response of $CO_{2_{Intensity}}$ to a digitalization shock over a 10-quarter horizon

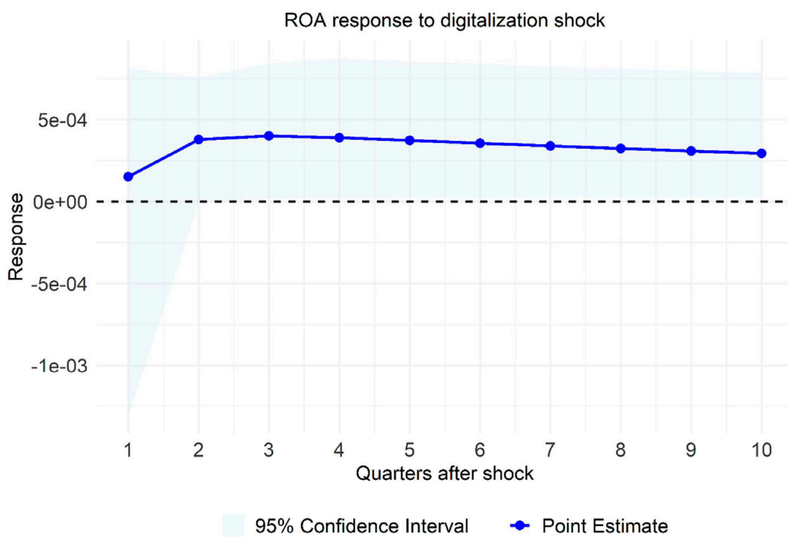

Fig. 3. Response of financial performance (*ROA*) to a digitalization shock over a 10-quarter horizon

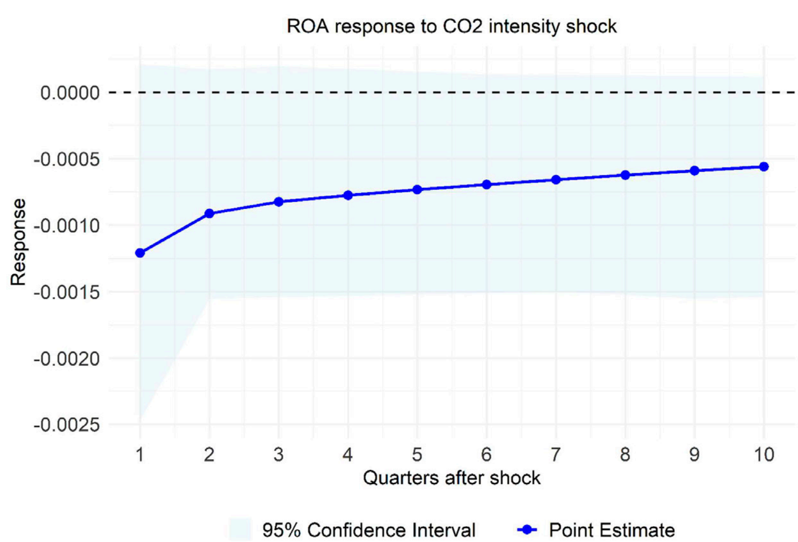

Fig. 4. Response of financial performance (*ROA*) to a $CO_{2_{Intensity}}$ shock over a 10-quarter horizon

Table 8

Hypothesis testing results

Hypotheses	Description	Result	Empirical evidence
H1	Digitalization's impact on environmental performance	Confirmed	Table 5, Fig. 2
H2	Digitalization's impact on financial performance	Not confirmed	Tables 5, 6, Fig. 3
H3	Environmental performance's impact on financial performance	Confirmed	Tables 5, 6, Fig. 4
H4	Digitalization's indirect impact through environmental performance	Received indirect empirical support	Summary of results from Tables 5–7 and Fig. 2–4. No formal test of indirect effect performed
H5	Presence of dynamic effects	Confirmed partially	Lagged OLS and PVAR. IRF results show limited statistical robustness

6. Discussion of the results of assessing digitalization's impact on environmental and financial performance

The results suggest that in energy companies, digitalization does not have a pronounced direct impact on financial performance but may be linked to it through environmental channels. The main outcome is increased digitalization's association with a decrease in carbon intensity while carbon intensity negatively impacts a company's financial performance. This logic is consistent with the results given in Tables 5–8 and Fig. 2–4.

Presented in Table 5, digitalization's statistically significant negative impact on carbon intensity can be explained by the fact that digital technologies enhance monitoring, control of production processes, resource management, and environmental accounting. Unlike [15], which analyzes digitalization across a broad sample of industrial enterprises, this study demonstrates this effect at the level of energy companies. Unlike [16] that reviews environmental performance through a multidimensional set of indicators, this study uses a specific indicator, carbon intensity.

The next key finding is carbon intensity's negative impact on ROA. Table 5 demonstrates this effect in the static model while Table 6 confirms it in the lagged specification. This means that environmental inefficiencies have financial consequences and can reflect asset depreciation, production losses, rising environmental costs, and weak operational efficiency. Unlike [26], which explores the general ESG effect, this study emphasizes a specific channel through which CO_2 intensity influences ROA. This finding is also supported by [30] that characterizes the relationship between decarbonization and profitability of energy companies as ambiguous.

Another important finding of this study is the lack of digitalization's direct, statistically significant impact on ROA. This is confirmed by both the fixed-effects model in Table 5 and the dynamic model in Table 6. Consequently, digitalization in capital-intensive energy companies does not act as a rapid financial driver. Its effect manifests itself through environmental and operational efficiency. In contrast to [10, 12, 13] that often treat digitalization as a direct factor in financial growth, our results show that this effect is not confirmed for the energy sector.

The environmental channel interpretation received empirical support based on the combined results. Tables 5–7 show how digitalization is associated with a decrease in carbon intensity, carbon intensity is negatively associated with ROA while digitalization's direct effect on ROA remains statistically insignificant. The impulse response functions complement this logic: a digitalization shock has a negatively directed response to carbon intensity, ROA's response to digitalization is weak and unstable, and a carbon intensity shock is linked to a decrease in ROA. Therefore, H1 and H3 received empirical support, H2 was not confirmed, H4 received indirect empirical support without a formal test of the indirect effect, and H5 was confirmed partially.

In contrast to [31, 32] that explain digitalization's financial impact through green innovation, operational efficiency, and cost reduction, this study examines carbon intensity as a possible environmental channel. This allows to move beyond the general logic of innovation mediation to a more specific mechanism whereby digitalization leads to a reduction in CO_2 intensity, which, in turn, is reflected in changes in ROA. The results are also consistent with [22, 23] that emphasize the fact that digitalization does not always produce a direct financial effect.

Accordingly, the study addresses the problematic issue identified in Section 2 whether the digitalization's impact on financial performance is direct or indirect. The results show that in the energy sector, direct financial effect is not confirmed while environmental channel receives indirect empirical support. This was made possible by using a quarterly panel, a text-based digitalization indicator, carbon intensity, and a dynamic econometric strategy.

This study's advantage lies in its shift from the general "digitalization – ESG – finance" framework to a more precise "digitalization – carbon intensity – ROA" mechanism. Unlike studies based on ESG indices, surveys, macro-level ICT indicators, or annual data, this paper uses a balanced panel of 220 quarterly observations and a combination of econometric methods, namely FE, lagged OLS, PVAR, and IRF.

From a practical perspective, the results indicate that energy companies should prioritize digital investments in environmental monitoring, carbon intensity management, automated emission control, and ESG reporting systems.

This study's limitations relate to the sample, variable measurement, and interpretation of results. The analysis covers five largest companies in the Republic of Kazakhstan's energy sector rendering the findings primarily applicable to large companies with a developed corporate reporting system.

The digitalization indicator is based on a text analysis of the reports and reflects the intensity of digital disclosure rather than actual volume of digital investments or implemented technologies. Its values may depend on the style of corporate disclosure, the structure of the reports, and the companies' communication policies. To mitigate this limitation, a uniform text cleaning procedure, a fixed dictionary of digital terms, and normalization of digital mentions to the total text volume were used.

Environmental performance is measured through carbon intensity. This is the reason this study ignores other environmental parameters like water consumption, waste, energy efficiency, and methane emissions. Furthermore, the carbon intensity indicator is primarily disclosed annually. In the quarterly panel, its annual values are distributed across the quarters of the corresponding year according to a uniform rule for all companies and are not interpreted as actual intra-year fluctuations.

Financial performance is represented by ROA that reflects an accounting assessment of the company's performance rather than a market one. Another limitation is the lack of differentiation by technology type. Furthermore, despite the use of FE, lagged OLS, PVAR, and IRF models, the results should be interpreted as robust econometric relationships rather than as experimental evidence of causality. H4 received only indirect empirical support based on the result consistency and a formal test of the indirect effect was not a part of the study.

The disadvantages of the study include the use of a text-based proxy for digitalization, which reflects the intensity of digital disclosure rather than actual digital investments or technology implementation. Another disadvantage is the limited differentiation of digital technologies, since the model does not separately assess the effects of artificial intelligence, automation, IoT, ERP systems, or digital platforms. In addition, the mediation mechanism is assessed indirectly through the consistency of static and dynamic results, while a formal mediation test is not performed. These disadvantages can be eliminated in future study by using data on actual digital investments, classifying digital technologies by type, expanding the range of environmental indicators, and applying formal mediation analysis.

Further development of this study may involve expanding the sample to include other energy and infrastructure companies, comparing the Republic of Kazakhstan with other resource-exporting economies, disaggregating digitalization by technology type, and incorporating additional environmental indicators such as methane emissions, energy efficiency, water use, and waste. However, such development may face several methodological and data-related difficulties. These include limited access to comparable quarterly environmental data, differences in corporate disclosure standards, inconsistencies in ESG reporting, and the difficulty of separating actual digital transformation from its textual representation in annual and sustainability reports. These challenges can be addressed by combining corporate reports with operational data, investment data, and standardized ESG disclosures.

7. Conclusions

1. A balanced quarterly panel dataset was compiled and validated for five companies in the Republic of Kazakhstan's energy sector for 2015–2025. The final dataset includes 220 observations: 5 companies, 44 quarters each. Descriptive statistics revealed significant interfirm and time-dependent variability in the indicators: ROA ranges between −0.0526 and 0.0659, carbon intensity between 0.0004 and 151.0000, and digitalization between 0.0001 and 0.2360. Correlation analysis revealed a negative relationship between digitalization and carbon intensity (−0.198), a negative relationship between carbon intensity and ROA (−0.343), and a weak direct relationship between digitalization and ROA (−0.059). The IPS test demonstrated stationarity of ROA and non-stationarity of digitalization and carbon intensity's logarithmic indicators, thereby justifying the use of dynamic models. This allowed to move from a static data description to assessing dynamic relationships over time.

2. The fixed-effects models of environmental and financial performance were evaluated using digitalization, carbon intensity, and control variables. In the environmental performance model, the logarithm of digitalization had a statistically significant negative association with carbon intensity ($\beta = -0.2828$; $p < 0.01$), indicating that higher digital disclosure intensity is associated with lower CO_2 intensity. In the financial performance model, the direct effect of digitalization on ROA was not statistically confirmed ($\beta = -0.0035$; $p > 0.10$), while carbon intensity had a significant negative association with ROA ($\beta = -0.0118$; $p < 0.01$). These results show that the environmental relationship is stronger than the direct financial relationship and provide a basis for further analysis of a possible environmental transmission channel.

3. Environmental performance was found to be significantly correlated with financial performance. Carbon intensity has a negative impact on ROA: in the fixed-effects model, the coefficient was −0.0118 at $p < 0.01$. The dynamic model confirmed this result as well: lagged carbon intensity negatively impacts current ROA with a coefficient of −0.00213 at $p < 0.05$. Therefore, high CO_2 intensity reflects not only environmental burden but also weaker operational efficiency, which then manifests itself in financial performance. This clarifies existing findings on the general relationship between ESG and financial performance as it reveals a specific environmental channel of influence on asset profitability.

4. It was found that the lack of statistically confirmed direct effect of digitalization on ROA. Digitalization's direct effect on ROA was not statistically confirmed in either the fixed-effects or dynamic models. However, the results suggest digitalization's more likely role as a tool for reducing environmental burden, through which an indirect effect on financial performance may be formed. Dynamic analysis further supports this logic; however, the IRF results require careful interpretation. PVAR revealed high persistence of digitalization (0.9144; $p < 0.01$) and carbon intensity (0.9321; $p < 0.01$), as well as a negative effect of lagged CO_2 intensity on ROA (−0.0089; $p < 0.10$). The impulse response functions showed directional consistency with the hypothesized mechanism but statistical robustness of individual responses is limited due to confidence intervals crossing zero. To summarize, H1 and H3 received empirical support, H2 was not supported, H4 received indirect empirical support without a formal test of the indirect effect, and H5 was supported partially. A dynamic structure was identified through lagged OLS and PVAR but IRF results have limited statistical robustness due to confidence intervals crossing zero.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

During the preparation of the manuscript, limited use of artificial intelligence tools was applied exclusively for grammar, spelling, and punctuation checking under full human control. Specifically, the GPT-5.5 language model (OpenAI) was used to assist in correcting language inaccuracies in individual sentences without generating or modifying scientific content.

The AI tools were not used for writing or generating any substantive parts of the manuscript, including the Introduction, Literature Review, Materials and Methods, Results, Discussion, or Conclusions, and were not involved in data collection, data analysis, interpretation of results, or formulation of scientific conclusions.

All text processed with the assistance of AI tools was manually reviewed, edited, and validated by the authors. The use of AI tools did not influence the study design, empirical results, or the conclusions of the study.

Authors' contributions

Zhaxat Kenzhin: Conceptualization, Methodology, Supervision, Writing – original draft; **Ali Sabyrzhan**: Methodology, Validation, Writing – review & editing; **Dinara Mussabalina**: Formal analysis, Investigation, Writing – original draft; **Aizhan Nurbaeva**: Data curation, Resources, Investigation; **Kenzhessulu Kuptleuova**: Resources, Data curation, Writing – original draft; **Natalya Lelesh**: Investigation, Visualization, Writing – original draft; **Andrey Shunko:** Investigation, Validation, Writing – review & editing; **Akmaral Zhakypova**: Validation, Visualization, Writing – review & editing; **Arman Maralov**: Software, Project administration, Funding acquisition, Writing – review & editing.

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