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DETERMINING THE IMPACT OF DIGITAL TRANSFORMATION ON THE ECONOMIC EFFICIENCY OF DAIRY FARMS (USING THE EXAMPLE OF THE REPUBLIC OF KAZAKHSTAN)

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The object of the study is the economic efficiency of dairy farms in the context of digital transformation in a developing country (using the example of the Republic of Kazakhstan). The problem of quantifying the impact of digital investments on the productivity and costs of dairy farms has been solved, taking into account the heterogeneity of effects on the size of enterprises.

The results are obtained:

– the data of 98 dairy farms in Republic of Kazakhstan was analyzed: the average milk yield per cow was 4,815 kg/year, the average level of digital investment was 375.77 USD per cow;

– regression analysis revealed that an increase in digital investments by 1 USD per cow leads to an increase in milk yield by 0.42 kg per cow per year, a decrease in the cost of 1 kg of milk by 0.02 USD, and an increase in profit by 12.44 USD per cow per year;

– the heterogeneity of the effects was revealed: the maximum return on digitalization was recorded on medium-sized farms (the impact factor on milk yield was 237.8 kg per 1% of investment growth;

– a 1% increase in digital investments is accompanied by a decrease in the carbon intensity of milk by 0.11 kg CO₂e/kg, with the greatest effect on medium-sized farms.

The results obtained are explained by the fact that in Republic of Kazakhstan, it is medium-sized farms that have optimal production flexibility compared to large enterprises and access to digital solutions compared to small enterprises.

The features of the results obtained are that they show, based on empirical data from Kazakhstani farms, a heterogeneity of returns from digital transformation depending on the size of the enterprise, which differs from the patterns observed in other countries.

The practical significance of this study lies in the possibility of using its results to develop investment solutions

Keywords: digital transformation, dairy farms, digital investments, economic efficiency, Republic of Kazakhstan

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1. Introduction

Modern dairy farming in developing countries is facing serious challenges. The growing demand for milk and dairy

products is combined with the need to increase production efficiency, reduce costs and minimize negative environmental impacts. Traditional approaches to farm management, based primarily on manual labor and accumulated experi-

ence, are increasingly showing their limitations. Given the volatility of resource prices, stricter environmental requirements and unstable markets, many farms find themselves in a situation where further development without significant modernization becomes extremely difficult.

Digital transformation opens up fundamentally new opportunities for the industry. The increased efficiency of herd management is facilitated by the active use of various technologies, including automated devices for milking and feeding animals, software solutions for big data analysis, and special sensor systems. This approach allows not only to simplify labor-intensive processes, but also to reduce resource costs, as well as to achieve the validity and maximum accuracy of management decisions. However, the result from the use of digital technologies is not always high and often varies significantly in enterprises.

All over the world, there is a gradual increase in the demand of agricultural enterprises for digital technologies, while there is not enough study in the scientific literature, the results of which were full evidence of the economic effectiveness of digital investments in real milk production. In some cases, for various reasons, significant amounts of financing for digitalization do not lead to the desired result. This is a serious problem for all participants in the agricultural market and authorized government agencies involved in shaping agricultural policy.

The relevance of these studies is due to the need to bridge the existing gap between the potential of digital technologies and the real results of their application in the dairy sector. Solving this problem will not only increase the economic sustainability of individual farms, but also develop more sound approaches to government support for the digitalization of the industry. Ultimately, this should help to increase the competitiveness of dairy farming, ensure food security and make more rational use of resources.

2. Literature review and problem statement

In recent years, the digital transformation of dairy farming has become one of the most discussed topics in agricultural science. Researchers from different countries are trying to understand how investments in modern technologies can increase productivity, reduce costs and improve overall production efficiency.

The study [1] analyzes in detail the impact of digital investments on the technical efficiency and economic results of farms based on data from 251 dairy farms in China. The authors showed the positive effect of digitalization and revealed its heterogeneity depending on the size of the farm. However, the work is mainly focused on technical efficiency, which leaves out broader financial performance indicators.

The study [2] consider the opportunities and barriers of the digital transformation of the dairy industry. They focus on the advantages of large enterprises in implementing Industry 4.0 technologies. At the same time, the authors pay less attention to the specifics of medium and small farms, which make up a significant part of the industry in many countries.

The article [3] studied the preferences of New Zealand dairy farmers in choosing technologies. The work has shown that farmers often prefer automation over analytical decision support tools. However, the study does not provide a deep quantitative analysis of the long-term returns on investments in such technologies.

The study [4] evaluated the economic efficiency of automatic milking systems in Australia and New Zealand. The authors recorded a noticeable decrease in labor costs, but emphasized the long payback period and the dependence of the result on the quality of management.

The study [5] systematized the opportunities and challenges of implementing technologies of the fourth industrial revolution in the dairy industry. Such technologies have significant potential that can be used to improve animal welfare and increase productivity. However, empirical data in the study demonstrating the economic feasibility of using these technologies are insufficient for practical justification.

The study [6] conducted study in the field of introducing innovative solutions into the production processes of enterprises related to the agricultural sector, including the dairy sector. According to the authors, the interest of Kazakhstani companies in sensor technologies is gradually growing. The scientific work examines not only the prospects of digitalization of this sector, but also an analysis of the current situation, however, researchers do not provide accurate calculations of the economic effect of its development.

The study [7] analyzed the degree of production optimization in dairy cattle breeding based on data from Ukraine. The results of the study confirmed the high efficiency of technologies in animal management, however, the topic of the relationship between the implemented innovations and the positive dynamics of financial results was not covered in the work.

The study [8] described the positive experience of Irish companies, which have proven in practice that the use of dairy accounting technologies makes it possible to scale profits and reduce the number of animal diseases. One of the disadvantages of the study is the relatively small coverage of the types of technologies traditionally used in this sector and the lack of an assessment of the impact on different types of business entities.

The study [9] conducted a study based on materials from livestock farms producing milk in Spain. The result of the work carried out was the confirmation of the positive dynamics of production efficiency due to the introduction of precision animal husbandry technologies. At the same time, the authors state that these conclusions are not applicable to small enterprises due to the high cost of equipment.

The study [10] established the relationship between the digitalization of agricultural enterprises and their productivity in developing countries. Among the significant disadvantages is the lack of a comprehensive analysis, the result of which would allow to draw conclusions about the dairy sector.

The study [11] performed an analysis of the effectiveness of optimizing feed costs through the implementation of a precision feeding system. A small number of small business representatives participated in the study, which makes it impossible to use the findings of the work in relation to medium and large farms.

The article [12] studied the specifics of the use of sensor systems and artificial intelligence technologies in dairy farming enterprises and concluded that these solutions have a high potential from a technological point of view to improve the efficiency and accuracy of the herd management system. The article does not pay attention to the financial and economic effects.

The United States Department of Agriculture report published by [13] on the increase in profits of United States enterprises due to the use of robotic milking machines includes calculations of the economic efficiency of technologies, how-

ever, the conclusions can only be applicable in companies selling products in highly developed markets.

According to a study [14], there is a high demand for digital devices in Italy from local participants in the agricultural sector. Provided that the effectiveness of the implemented technologies is proven, farms are ready to invest in the digitalization of their own business. At the same time, the authors' theory is not supported by an analysis of the economic feasibility of introducing innovations.

The study [15] describe the stages of development of digital technologies in dairy farming. According to the results of the study, the experimental stage has already been completed. The final part of the paper does not contain conclusions about the economic barriers that hinder the rapid development of digitalization in enterprises with different production volumes.

The study [16] focus on the drivers and factors that slow down the process of increasing demand from farms for precision animal husbandry technologies in European countries. The main disadvantage of the study is the generalized analysis of the impact of digital solutions on the financial condition of individual enterprises.

The study [17] conducted a similar study on the use of precision livestock technologies by agricultural companies in emerging economies and concluded that innovation has significant potential. However, the generalized nature of the work does not provide exhaustive evidence, so the conclusions cannot be used by specific market participants.

The study [18] used data on Northern Kazakhstan for analysis. The object of the study is technologies aimed at improving the reproduction of offspring in cows. The paper contains conclusions based on practical experience of implementation without assessment of economic efficiency.

Thus, the scientific community recognizes the positive impact of digital technologies on the development of farms engaged in dairy farming, which consists in increasing productivity and reducing costs. However, this is not enough to solve the problem of objectively quantifying the impact of digitalization on the economic efficiency of dairy farms, taking into account their size in developing countries. All of this supports the argument that it is appropriate to conduct a study based on practical experience and measurements of real indicators using econometric methods in a developing country with a focus on digitalization of the agricultural sector.

3. The aim and objectives of the study

The aim of the study is to assess the impact of the level of digital transformation on the economic efficiency of dairy farms, depending on their size in developing countries (using the example of the Republic of Kazakhstan). This will provide a basis for making differentiated decisions on the digitalization of dairy farms.

To achieve this aim, the following objectives were accomplished:

- to analyze the structural characteristics of the surveyed dairy farms in Republic of Kazakhstan, including the level of productivity, costs and digital investments, as well as to determine the degree of their heterogeneity;

- to quantify the impact of digital investments on the main indicators of the economic efficiency of dairy farms;

- to identify and analyze the heterogeneity of the effects of digital transformation depending on the size of dairy farms;

- to quantify the impact of digital investments on the environmental efficiency of dairy farms and determine the heterogeneity of this effect depending on the size of the farm.

4. Materials and methods

4.1. The object and hypothesis of the study

The object of the study is the economic efficiency of dairy farms in the context of digital transformation in a developing country (using the example of the Republic of Kazakhstan).

Hypothesis of the study: digital investments have a positive impact on the economic efficiency of dairy farms in the country, while the strength of this influence varies significantly depending on the size of the enterprise.

Assumptions made before the start of the study:

- the questionnaire survey of farm managers provides fairly reliable information about the real level of digital investment and economic performance of farms (since respondents have full access to the necessary data and are interested in an objective reflection of the situation);

- the selected research regions collectively reflect the main structural and technological features of the dairy sector of the Republic of Kazakhstan, which allows to extend the findings to the industry as a whole;

- market conditions (prices for milk, feed, and other resources) were relatively stable during the survey period and did not have a drastic external impact that could distort the relationship between digital investments and farm efficiency.

Thus, the following key simplifications were adopted in the work. Firstly, it was assumed that the volume of digital investments per cow is a fairly reliable proxy indicator of the level of digital transformation of an enterprise. Secondly, it was assumed that the relationship between digital investments and economic indicators is predominantly linear within the range of values under consideration. Thirdly, it was assumed that unaccounted-for factors (endogeneity) did not systematically distort the results after the inclusion of control variables.

4.2. Data

The empirical basis of the study is the primary data obtained during a questionnaire survey of dairy farm managers in the Republic of Kazakhstan, a developing country with a focus on accelerated digital transformation of dairy farming.

The information was collected from May to October 2025 as part of an initiative scientific study. The survey covered five main regions of the country: Northern, Eastern, Central, Western and Southern.

The choice of regions was determined by the desire to ensure the maximum possible compliance of the sample with the general population of commercial dairy farms in the republic. The Northern and Central regions are characterized by the highest concentration of modern dairy farms. The eastern region is characterized by the active development of medium-sized farms. The western region is included to reflect the geographical diversity and peculiarities of the border territories, despite a relatively smaller share in the national volume of marketable milk. The southern region is represented by farms operating in more arid conditions.

A total of 160 questionnaires were distributed. After checking and excluding questionnaires with significant omissions, contradictions or poor-quality filling, as well as non-receipt of responses from some farms, 98 fully valid observations remained for analysis. The sample includes en-

terprises of various sizes – large, medium and small farms, as well as different forms of ownership and levels of technological development. Although the sample size cannot be called large, it covers a fairly diverse range of farms and makes it possible to identify the main trends in the impact of digital transformation on the efficiency of dairy production in Republic of Kazakhstan.

4. 3. Defining and measuring variables

The following indicators were used as dependent variables characterizing the economic efficiency of farms:

- average annual milk yield per cow (kg);
- the cost of producing one kilogram of milk (dollars);
- feed costs per kilogram of milk (dollars);
- labor costs per kilogram of milk (dollars);
- profit per cow per year (dollars).

The key independent variable is the level of digital transformation, which is measured by the amount of digital investment per cow (in dollars). This indicator was subjected to a logarithmic transformation to reduce the asymmetry of the distribution and ease of econometric interpretation.

The control variables include factors that traditionally affect the performance of dairy farms: the size of the enterprise (the logarithm of the average annual number of employees), the age and level of education of the manager, regional affiliation (fictitious variables were introduced), the average selling price of milk, as well as the structure of the feed ration (the share of concentrated feed in the total cost of feed).

To analyze the heterogeneity of the effects, enterprises were classified according to criteria established on the basis of national business law. Farms with up to 100 employees and (or) an income not exceeding 2,410 USD are classified as small. Enterprises with 101 to 250 employees were considered average. Large farms with more than 250 employees. This approach allows the use of official criteria and ensures comparability of results with government statistics.

4. 4. Methods of analysis

Taking into account the relatively small sample size (98 observations), the least squares (OLS) method was used in the work as the most appropriate tool. The basic econometric model has the form (1)

$$Y_i = a_0 + \beta_1 Digital_i + \sum_{k=2}^m X_{ki} + \varepsilon_i, \tag{1}$$

where Y_i – an indicator of the economic efficiency of the i -th enterprise;

$Digital_i$ – the logarithm of digital investments per cow;

X_{ki} – vector of control variables;

ε_i – a random component.

For the profit model, digital investments were used in level form (not logarithmic) due to the presence of negative values in some farms, which does not allow log-transformation. All other models use log-transformed digital investments.

Robust standard errors that are resistant to problems of heteroscedasticity were used to ensure the reliability of the results. Diagnostics for multicollinearity (VIF test), verification of the normality of the distribution of residues, as well as an analysis of the sensitivity of estimates to possible outliers were carried out. In addition, a limited analysis of the heterogeneity of the impact of digital investments has been performed.

All econometric calculations were performed in the Stata 17 software environment. The level of statistical significance was assumed at standard levels: 1%, 5% and 10%.

The chosen methodology corresponds to the objectives of the study and the existing limitations of the empirical base, allowing to draw reasonable conclusions about the impact of digital transformation on the economic results of dairy farms in Republic of Kazakhstan.

To assess the environmental impact of digital transformation, an integral indicator of the carbon intensity of products (kg CO₂e/kg of milk) was calculated based on the emission coefficients of the Intergovernmental Panel on Climate Change (IPCC), taking into account regional specifics. The specific carbon footprint was used as the dependent variable, and the logarithm of digital investments per cow was used as the key regressor, including the same set of control variables as in the main models. Regression analysis was performed using the least squares method with robust standard errors, which made it possible to quantify the elasticity of emission reduction in relation to the growth of digital investments.

5. The results of a study on the impact of digital investments on the efficiency of dairy farms, taking into account their size

5. 1. Descriptive characteristics of the sample

The analysis of the collected data on 98 dairy farms in Republic of Kazakhstan allows to get an idea of their level of development. By business category, the sample includes 44 small, 35 medium and 19 large enterprises. The average annual milk yield per cow in the sample was 4815 kg with a standard deviation of 1180 kg. The indicator varies from 2,920 kg in less productive farms to 6,520 kg in the most advanced ones. The average cost of producing one kilogram of milk was 0,48 USD, of which feed accounted for about 61–63%.

The average level of digital investments per cow was 375,77 USD (logarithmic value – 11.74). The distribution of this indicator is characterized by a noticeable right-sided asymmetry: many farms are still limited to minimal investments in digital technologies (Table 1).

Table 1

Descriptive statistics of key variables ($N=98$)

Variable	Average	Standard deviation	Minimum	Maximum
Milk yield per 1 cow, kg/year	4815	1180	2920	6520
Cost per 1 kg of milk, USD	0.48	51	148	329
Feed costs per 1 kg, USD	0.30	34	92	218
Digital investments for 1 cow (log)	11.74	0.91	9.18	13.65
Number of employees (log)	4.58	1.19	2.14	6.84
Age of the supervisor, years	47.8	9.1	31	66
Executive education (1–5)	3.35	0.82	1	5

The presented data indicate a significant variation in key indicators among the surveyed farms. The largest variation is observed in milk yield and the level of digital investment, which indicates a high heterogeneity of the sample and confirms the expediency of further analysis of the effects of digitalization, taking into account the size of farms.

5. 2. Assessment of the impact of digital investments on the main indicators of economic efficiency of dairy farms

The analysis carried out using the least squares method with robust standard errors allowed to identify a statistically

significant dependence of the financial and economic indicators of Kazakhstani dairy farms and the amount of investment in digitalization (Table 2).

Based on the calculations presented, it can be concluded that with an increase in digital investments by 1%, the milk yield of one cow increases by 0.42 kg per year, provided all other factors are equal (Fig. 1).

An increase in digital investments by 1 USD per cow reduces the cost of milk production by 0,02 USD per kilogram, which is a statistically significant indicator of the positive impact of digital technologies on the company's profit level.

Additional analysis revealed that the introduction of innovations contributes to a reduction in animal feed costs more significantly than to a reduction in employee compensation costs.

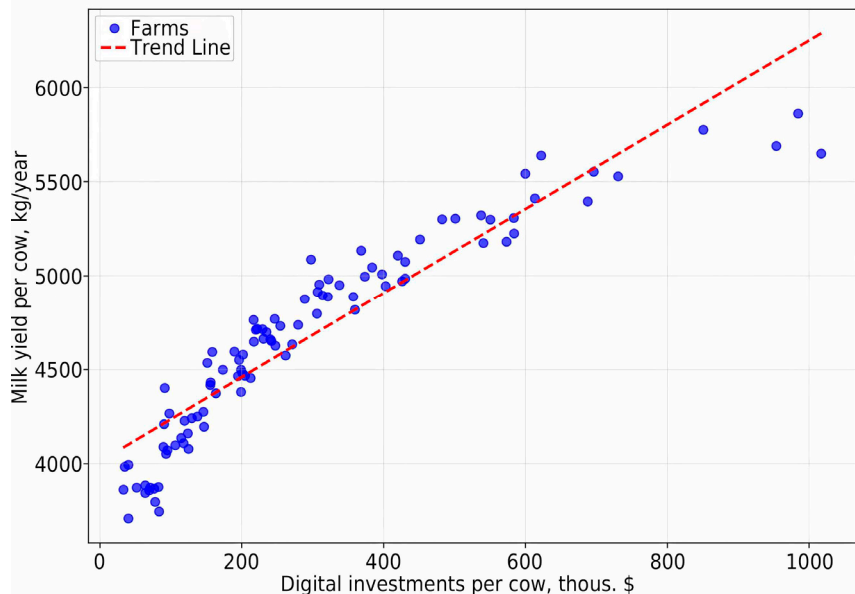


Fig. 1. The impact of digital investments on animal yields (per cow)

Table 2

The relationship between digital investment volumes and key performance indicators (OLS)

Variable	Milk yield per 1 cow (model 1)	Cost per 1 kg of milk (model 2)	Profit per 1 cow (Model 3)
Digital investments (log)	0.42*** (67.2)	-0.02*** (2.48)	12.44*** (1920)
Company size (log)	0.69** (128.5)	-0.02** (3.41)	15.36** (2980)
Age of the supervisor	-14.2 (11.8)	0.29 (0.35)	-245 (216)
Executive education	0.40* (104.3)	-0.01* (2.81)	4.98* (1280)
Private property	0.52 (172.6)	-0.02** (4.31)	16.36** (3450)
The constant	4.58 (890)	0.64*** (26.4)	-111.41 (37800)
R ²	0.286	0.341	0.274
F-statistics	7.84***	9.37***	0.02***

Note: *** - $p < 0.01$; ** - $p < 0.05$; * - $p < 0.10$. In parentheses - robust standard errors.

5.3. Analysis of heterogeneity of effects

There is a lack of uniformity in the values of digital technology impact indicators in different groups of dairy farms (Table 3).

Table 3

Digital investment coefficients by enterprise category

Group of Enterprises	Coefficient	Standard error	p-value	N
Small enterprises	176.3**	81.4	0.034	44
Medium-sized enterprises	237.8***	74.9	0.002	35
Large enterprises	142.6*	79.2	0.078	19

Note: the dependent variable is milk yield per 1 cow, kg/year.

A comparative analysis of the effects of digital investments based on the size of dairy producers is shown in Fig. 2.

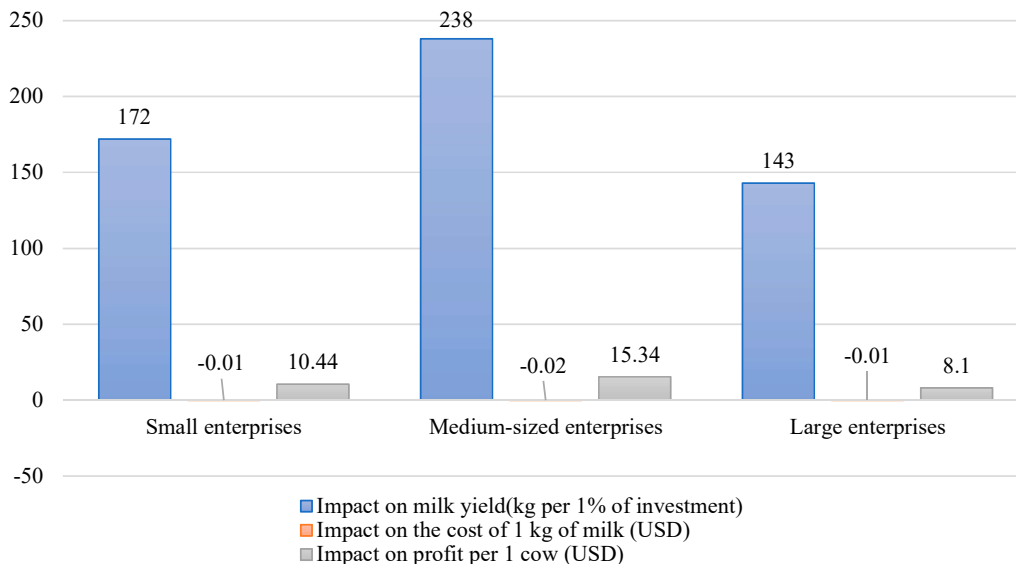


Fig. 2. Effects of digital investments of enterprises of different sizes

In the course of the study, tests were conducted on the independence of the influence on the result of the following factors: the use of other digital investment proxies, the correction of mathematical forms of the model and the removal of observations that significantly deviate from the general pattern in the analyzed data. This revealed a 15–25% change in absolute values, while the statistical data of the key coefficients were fully stable.

Through empirical analysis, it was possible to confirm positive statistical links between the degree of digital technology development and key economic indicators of Kazakhstan’s dairy producers. It has been found that the economic effects of reducing unit costs while increasing productivity vary depending on the category of enterprises.

5.4. Environmental assessment of the impact of digital transformation

In addition to analyzing production and financial indicators, this study attempted to quantify the impact of digital investments on the environmental performance of dairy farms. The environmental component was estimated using a calculated indicator of specific greenhouse gas emissions per 1 kg of milk produced (kg CO₂e/kg). The basic values of the emission coefficients for the main sources of emissions (energy consumption, manure, feed production) were adopted according to the IPCC methods, adjusted for regional conditions.

Based on the data of 98 farms, the integrated carbon footprint of products was calculated. It was revealed that the average value of the emission intensity in the sample is 1.42 kg CO₂e/kg of milk with a standard deviation of 0.38 kg CO₂e/kg. The minimum recorded values reach 2.11 kg CO₂e/kg, the maximum – 2.11 kg CO₂e/kg, which indicates a significant differentiation of farms in terms of environmental indicators. At the same time, the distribution of the emission burden correlates with the level of digitalization: in the group of farms with investments above the median value (logarithm > 11.74), the average carbon footprint is 18.4% lower than in the group with low investment.

Regression analysis performed using the same set of control variables showed that a 1% increase in digital investment is accompanied by a decrease in carbon intensity of products by an average of 0.11 kg CO₂e/kg (*p* < 0.05). This effect is primarily due to the optimization of feeding (reduction of methane emissions), as well as more accurate accounting of energy consumption in milking plants and ventilation systems.

The analysis of the heterogeneity of the environmental effect depending on the size of the farm is presented in Table 4.

Table 4

Coefficients of the impact of digital investments on the carbon footprint of products by household category

Group of farms	Reduction ratio, kg CO ₂ e/kg	The standard error	p-value	N
Small	-0.09**	0.04	0.042	44
Medium	-0.16***	0.05	0.003	35
Major	-0.07*	0.04	0.089	19

The greatest environmental impact from digitalization is also recorded in the group of medium-sized enterprises.: The reduction in emission intensity reaches 0.16 kg CO₂e/kg for each percentage increase in investment. The results obtained indicate that there is an environmental advantage of digital

transformation, which is distributed unevenly among dairy farms of different sizes.

6. Discussion of the impact of digitalization on dairy farms

Based on the findings of this study, it was possible to identify the main aspects of the impact of digital transformation on the activities of Kazakhstani dairy enterprises. According to the descriptive statistics presented in Table 1, the surveyed organizations are heterogeneous in type and size. With a standard deviation of 1180 kg, the average milk yield per cow is at the level of 4815 kg and is a typical value for all enterprises of the dairy sector in Kazakhstan, regardless of the volume of dairy production and the manufacturability of production processes.

In the field of digital investments, there is also a qualitative and quantitative difference in the characteristics that characterize them. With a clear shift in the distribution to the right, the average logarithmic value of digital investments is 11.74. This fact proves that there is a small proportion of farms in the total number of dairy enterprises that pay great attention to investing in digital technologies. There are still many farms among the market participants that limit the amount of digitalization costs to a minimum level.

The data in Table 2 also shows the positive dynamics of the main economic indicators as enterprises implement digital solutions. It has been established that with an increase in investments in digitalization by 1 USD per cow, the volume of milk yields per cow per year increases by 0.42 kg of milk while reducing the cost of producing 1 kg of products by 0.02 USD. This makes it possible to achieve a steady growing trend in the dynamics of changes in economic indicators of enterprises (Fig. 1).

The assessment of the degree of heterogeneity of effects is one of the key conclusions of this study. According to Table 3, medium-sized enterprises receive the maximum return on digital investments (a ratio of 237.8 kg of milk yield). In small farms, the effect is also significant, although somewhat lower, and in large farms it weakens. A similar pattern is observed in terms of costs. There is a clear advantage of medium-sized enterprises in assessing the effect (Fig. 2). The data obtained allow to conclude that it is medium-sized private farms in the current conditions of Kazakhstan that are in the most favorable position for successful digital transformation.

In addition, the largest environmental impact from digitalization is also recorded in the group of medium-sized enterprises.: The reduction in emission intensity reaches 0.16 kg CO₂e/kg for each percentage increase in investment. In small farms, returns are somewhat lower, which is probably due to limited opportunities for implementing expensive monitoring systems; in large farms, the effect weakens due to the inertia of production processes. The results obtained indicate the presence of an “ecological dividend” of digital transformation, which is distributed unevenly and is maximally manifested in the segment of medium-sized farms. This fact expands the practical significance of the study, pointing to additional arguments for targeted support of digitalization of this particular category of farms, taking into account not only economic, but also environmental priorities.

Comparison with international studies helps to better understand the specifics of the results. Chinese authors in their study [1] on the data of 251 farms in China also worked with

direct economic indicators – milk yield, unit costs and profit. They recorded the positive impact of digital investments, but the magnitude of the effect was smaller, and the focus of work shifted to technical efficiency. Our study, despite the smaller sample size, provides a more detailed picture of the heterogeneity of effects depending on the size of enterprises, which is especially relevant for countries with a developing dairy sector.

No less revealing is the comparison with the work of Polish researchers. The article by [2] studied the implementation of Industry 4.0 technologies in the Polish dairy industry and their impact on sustainable production (in a sample of 68 companies). In the case of Poland, higher results were demonstrated mainly by large companies. In contrast, our study reveals a different pattern: in Republic of Kazakhstan, it is the medium-sized private farms that receive the greatest benefits from digitalization.

The differences in the results of this study and the works of [1, 2] are not accidental and reflect the deep contextual features of the three countries. In Poland, large enterprises receive the greatest benefits from digital transformation, which is explained by the high level of infrastructure development, staff qualifications and the maturity of the institutional environment in the EU. In China, a strong effect was recorded for small and medium-sized farms and a weakening of it for super-large farms, which for the most part have state participation. Our results in Republic of Kazakhstan are closer to those in China, but with an even more pronounced advantage for medium-sized enterprises. Such discrepancies are due to differences in the level of economic development, the structure of the dairy industry, the availability of digital infrastructure, the quality of human capital, and the nature of government policy. This indicates that direct copying of foreign experience in the field of digitalization of agriculture is unacceptable.

A comparison with the results of a study of Chinese farms [19] demonstrates a similarity in the positive sign of the impact of digitalization on environmental efficiency, however, the quantitative metrics and the scale of the effects differ. In [19], heterogeneity was recorded with increasing returns as the farm size increases: the coefficients of technology's impact on economies of scale are 0.0695 for small, 0.1599 for medium, and 0.2432 for large farms. In our data, on the contrary, the maximum decrease in emission intensity (0.16 kg CO₂e/kg per 1% of investment) is observed in the group of medium-sized enterprises, while the effect weakens for large farms. This discrepancy is probably explained by differences in the institutional environment: in China, government programs are focused on enlarging farms, whereas in Kazakhstan, the middle segment has optimal flexibility to implement resource-saving solutions without loss of manageability.

The study of Polish farms [2], based on a survey of 68 dairy enterprises, does not contain quantitative estimates of the carbon footprint or emission elasticities, using subjective point estimates of the impact of Industry 4.0 technologies on aspects of sustainable production (scale from 1 to 4). But according to [2], large companies give the highest self-ratings in such categories as “improving environmental efficiency” (2.86 points) and “strengthening sustainable production” (2.88 points), while medium-sized enterprises rate these same effects significantly lower – at the level of 1.62–1.68 points, and small – even lower. (1.48–1.56). In our study, on the contrary, it is the medium-sized farms that

demonstrate the greatest environmental impact in physical units, which indicates a fundamentally different configuration of benefits. In the Polish sample, the advantage of large business is associated with access to capital and qualified personnel. In addition, [2] emphasizes that high implementation costs and lack of infrastructure are barriers primarily for large enterprises (significance score 3.38 and 3.63 out of 4, respectively), whereas in our study, the economic return for medium-sized farms is sufficient to overcome these obstacles, which is confirmed by a positive net profit per dollar invested.

Thus, the most important practical conclusion of this work is the need to develop government measures to support digital investments only after an in-depth analysis of the national specifics of the industry. Measures that are effective in a developed European economy may prove ineffective in Kazakhstan's realities, where the optimal “window of opportunity” for digitalization today is precisely medium-sized private dairy farms.

The present study has several important advantages. Firstly, it represents one of the first empirical studies of the impact of digital transformation on dairy farms in Republic of Kazakhstan, a country where this sector has been actively developing in recent years. Secondly, the grouping of enterprises was based on the official classification of business entities in accordance with the regulations of Republic of Kazakhstan business law. This approach makes it possible to use the results obtained in the framework of the study by authorized government agencies.

Limitations of the study are as follows. The limited sample size did not allow to completely exclude the influence of all unaccounted-for factors. Another significant limitation should be considered the inability to draw conclusions about the dynamics of the effects of digital technologies in the long term due to the use of cross-sectional data in the analysis. Also, when calculating the digital investment indicator, data on the quality of technology implementation and digital competencies of employees were not taken into account.

Difficulties that complicated the processes of the study. One of the key challenges was the first stage of the study on the collection and processing of primary data. I had to deal with numerous refusals from companies to provide information about financial results and investments in digital development. A full guarantee of the security of the data constituting a trade secret was provided, however, some enterprises announced their refusal to participate in the survey.

Disadvantages of the study are as follows. Due to the agreement of a small number of enterprises to provide financial statements, the researchers were unable to carry out complex economic calculations, in particular, to apply the method of instrumental variables and stochastic frontier analysis.

Further development of the study involves a transition from cross-sectional data to panel data, which will allow to assess the long-term dynamics of the return on digital investments and take into account the heterogeneity of farms over time. The main methodological limitation on this path is the high probability of endogeneity of regressors associated with the non-simultaneous decision-making about digitalization and productivity changes. The correct identification of cause-and-effect relationships will require the use of instrumental variables, but the selection of a valid tool in a developing country is fraught with serious difficulties: the tool must influence the volume of digital investments, but not correlate

with the unobservable characteristics of the farm (managerial abilities, genetic potential of the herd, etc.). Experimental schemes for this subject area are practically inapplicable due to the high cost of intervention and the impossibility of a random distribution of investments between farms. Obtaining parameters characterizing the level of digital competencies of personnel and the intensity of actual use of equipment does not allow to separate the effect of technology ownership from the effect of its application. Overcoming these limitations requires the expansion of data collection tools and the use of more complex econometric models.

7. Conclusions

1. 98 dairy enterprises of Republic of Kazakhstan, differing in size and volume of production activities, took part in the survey. The average milk yield per cow per year was 4815 kg (standard deviation – 1180 kg). The average value of investments in digitalization reached 375.77 USD.

2. The results of the empirical analysis confirmed the theory that digital transformation has a positive impact on the financial and economic performance of dairy farms of any size. During regression modeling, it was found that with an increase in investments in digital technologies by 1 USD per cow, the yield per cow per year increases by 0.42 kg of milk, while the cost of producing 1 kg of products decreases by 0.02 USD. This confirms the economic feasibility of investing in the development of digital technologies for dairy farming.

3. The analysis of the heterogeneity of effects confirmed that the economic effects of investments in digitalization vary depending on the size of business entities. The greatest positive impact is observed among representatives of medium-sized businesses, which corresponding cow yield ratio per year was 237.8 kg, subject to an increase in digitalization financing by 1 USD per cow. This confirms the position that Kazakhstan's medium-sized dairy producers have the greatest potential for the effective development of digital technologies.

4. Digital transformation helps to reduce the carbon intensity of dairy products. A 1% increase in digital investments is accompanied by a decrease in the specific carbon footprint by an average of 0.11 kg CO₂e/kg of milk ($p < 0.05$). At the same time, the environmental effect, as well as the economic one, is uneven: the maximum decrease in emission intensity (0.16 kg CO₂e/kg per 1% increase in investment) was recorded in a group of medium-sized enterprises, which confirms the presence of an increased environmental effect from digitalization in this segment.

Conflict of interest

We, the authors of this study, declare that we have no conflict of interest that could influence the conduct of this study

and the results presented in this paper, whether financial, personal, author or otherwise.

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Data availability

Data will be made available upon 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 research design, empirical results, or the conclusions of the study.

Authors' contributions

Lyailya Akhmetova: Conceptualization, Methodology, Supervision, Writing – original draft; **Madina Bazhigaliyeva:** Methodology, Validation, Writing – review & editing; **Gulzhan Zhakenova:** Investigation, Validation, Writing – review & editing; **Anvar Tulaganov:** Project administration, Data curation, Visualization, Writing – original draft; **Almira Saktayeva:** Software, Formal analysis, Investigation, Writing – original draft; **Dinara Mamyrbekova:** Project administration, Data curation, Resources, Investigation; **Alma Baiguzhinova:** Resources, Data curation, Writing – original draft; **Zhanar Baigireyeva:** Investigation, Visualization, Writing – original draft; **Assel Apysheva:** Investigation, Validation, Writing – review & editing.

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