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Innovative approaches to enhancing the safety and resilience of dairy products under market challenges

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Abstract

Against the backdrop of increasing anthropogenic pressure on the environment, ensuring the quality of food products is becoming increasingly important as a key factor in safeguarding public health. This study focuses on improving dairy production processes through the implementation of integrated approaches aimed at enhancing microbiological safety at various stages of the technological cycle. The research assessed the impact of introducing technological and sanitary innovations on the quality indicators of raw milk and the economic efficiency of Promin Agricultural Limited Liability Company in the Mykolaiv Region during 2024–2025. The study evaluated the impact of probiotic feed supplements and improved milking equipment cleaning protocols on milk quality and economic efficiency in Holstein cows. The results showed a 47% reduction in total bacterial contamination and a decrease in somatic cell count from 390,000 to 210,000 per mL, leading to fewer losses during primary processing. The proportion of non-standard milk batches decreased by 31%. Improvements in microbiological stability were matched by better physicochemical parameters: density, freezing point, and acidity remained within regulatory limits, while protein content rose from 3.2% to 3.5%. The improved quality boosted the average milk procurement price by 8%, increasing profitability. Additionally, antibiotic use decreased, and economic analysis revealed a 15% reduction in detergent costs, 10% in energy consumption, and 30% in product losses. Thus, the implemented innovative solutions proved effective and can be recommended for use not only by dairy farm specialists but also by veterinarians, certification authorities, and researchers in the agricultural sector.

Keywords Bacterial contamination, Productivity, Animal health, Improvements, Microbiological indicators, Probiotics

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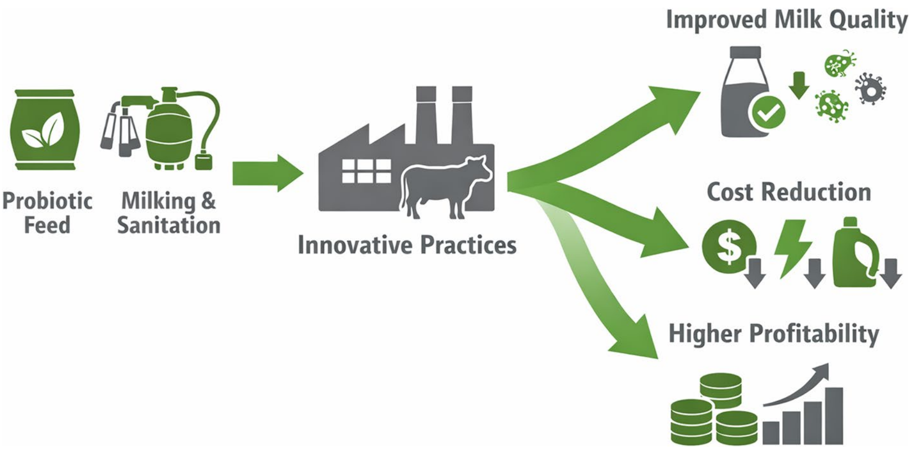
Graphical Abstract



Introduction

With the intensification of production and the growing technological requirements for the quality of raw milk, ensuring the microbiological safety and stability of the physicochemical parameters of cow's milk has become a pressing challenge within the dairy industry. Numerous studies highlight the importance of genetic and veterinary management in extending the productive lifespan of dairy cows, which in turn has a positive impact on the economic performance of farms. In particular, research by Tunisian scholars Sdiri et al. (2023), who focused on Holstein dairy cows, emphasised the significance of a range of influencing factors, such as animal health, environmental conditions, housing standards, and others, on both productivity and longevity. At the same time, the researchers noted that the introduction of innovative technologies in the agricultural sector of developing countries can contribute to improving their economic performance. These approaches can be adapted to Ukrainian conditions through a set of measures aimed at herd health improvement, better feeding practices, and the modernisation of hygiene and cattle health monitoring systems.

At the same time, considerable attention in the literature is devoted to refining diagnostic approaches and therapeutic management of mastitis, which remains one of the major challenges in dairy farming. The application of modern diagnostic and treatment methods helps to reduce incidence rates and improve milk quality. However, as highlighted by Kour et al. (2023), who examined this issue from a veterinary perspective, the search for alternatives to antibiotic therapy in managing bovine diseases remains highly relevant. Their review underlines the drawbacks of antibiotics, both due to the rapid emergence of resistance and the risk of subsequent chemical contamination of food products. This underscores the need for alternative strategies to maintain herd health on farms.

Studies conducted in EU countries have shown that the success of dairy enterprises largely depends on the adoption of innovative technologies, optimisation of production processes, and compliance with quality standards. For instance, Savickienė and Galnaitytė (2024) reported differences in the development of the dairy sector across European countries, which may indicate the potential for establishing export links and mutually beneficial cooperation with Eastern European states. According to the Slovak experience described by Kapsdorferova et al. (2023a), innovation in agriculture is also regarded as a tool for reducing food losses and improving the efficiency of agricultural production. Consequently, to meet the growing demands for food quality and to maintain enterprise competitiveness, it is essential to modernise technological approaches at different stages of production.

The economic resilience of the dairy sector is generally considered a key factor in its development, as confirmed by analyses of milk and dairy supply chains in various countries. For example, Milić et al. (2023) identified correlations between the quality of dairy products and the profitability of agricultural enterprises. They also observed that state support facilitated stronger sectoral growth, as reflected in comparative export data from different European countries. Similarly, the study by Kilima et al. (2024) provided important contextual insights into the role of institutional support, process standardisation, and food safety policies, all of which are equally critical for the dairy industry in Ukraine. An examination of the East African experience, particularly a review conducted by Tanzanian researchers, revealed that insufficient technical support, a fragmented supply chain, and a low level of safety standard integration limited the effectiveness of quality control systems at the farm level. This leads to the conclusion that, without the implementation of integrated technological solutions, achieving stable production and milk quality indicators remains a considerable challenge. A crucial factor is the ability of producers to adapt to contemporary requirements for sustainable development, to implement environmentally safe technologies, and to comply with international standards (Sirenko et al., 2024).

However, most existing studies have concentrated on individual components of the production chain, such as breeding, feeding, or hygiene, while overlooking their interconnection and the overall economic impact on producers (Gill et al., 2021; Gritsienko et al., 2022). There has also been a shortage of applied research that takes into account the specific conditions of agricultural enterprises with limited resources operating in volatile markets.

The novelty and contribution of this study lie in the development and evaluation of an integrated dairy safety management model that combines the addition of probiotic feed additives, improved sanitary conditions and equipment modernization, automated real-time milk quality monitoring, and economic performance evaluation on a single large commercial dairy farm. Unlike previous studies, which considered these measures separately, this study demonstrates their synergistic effect on improving the microbiological quality of raw milk, reducing somatic cell counts, increasing milk yields, and improving economic efficiency. By quantitatively assessing both microbiological and economic outcomes, including cost savings and payback periods, the study provides a scalable and practical framework for dairy enterprises, especially in emerging and economically unstable markets.

This study aimed to evaluate an integrated dairy safety improvement programme, combining probiotic supplementation and upgraded hygiene/sanitation practices, by assessing changes in microbiological and physicochemical milk quality indicators, animal productivity, and economic performance at a large commercial dairy farm.

Materials and methods

Study area and sample collection

The research was conducted between January 2024 and March 2025 at the Promin agricultural limited liability company (Mykolaiv Region, Ukraine), which specialises in the production of extra-grade milk and maintains approximately 11,400 head of cattle, including 4,700 Holstein dairy cows. The enterprise's production cycle includes a modern milking system, an automated line for primary milk processing and cooling, as well as an integrated system of veterinary and hygienic control. Within the framework of the study, 150 samples of raw milk, 150 samples of pasteurised milk, 100 swabs from technological equipment, 50 water samples, and 75 feed samples were collected and analysed. Sample collection was carried out in accordance with standards for assessing the quality, safety, and stability of dairy products at different stages of the technological process (State Service of Ukraine on Food Safety and Consumer Protection, 2024).

Research stages

The study was conducted in three stages, each aimed at evaluating and implementing various technological and biotechnological interventions to enhance the safety and quality of dairy products. Table 1 summarises the actions undertaken at each stage and clarifies the two evaluation components of the study (animal-level probiotic cohort and process-level, farm-wide sanitation/monitoring) and the baseline versus post-implementation comparison used to assess effectiveness.

The study implemented a combination of measures, including probiotic supplementation, improved sanitation practices, equipment upgrades, and adjustments

Table 1 Summary of research stages and changes implemented

Stage	Period	Key actions	Animal-level evaluation	Process-level evaluation
Stage 1: Baseline Evaluation	1 month	Baseline documentation and sampling	30 Holstein cows: baseline (pre-probiotic) measurements	Baseline sampling (milk, swabs, water, feed); existing sanitation recorded
Stage 2: Implementation of Innovative Measures	8 months	Implementation of integrated measures	Probiotics added to concentrate via automated dosing; monitoring continued	Updated sanitation regimen and Milkline DMS installed; continued sampling at control points
Stage 3: Assessment of Effectiveness	5 months	Effectiveness assessment	Re-evaluation (e.g., Day 60) and comparison with baseline	Post-implementation sampling and economic analysis; compared with baseline

Source: compiled by the authors

to the feeding regime. As all these interventions were introduced simultaneously, it was difficult to assess the isolated effect of each individual factor. To address this, the study was conducted in three stages. The first stage (1 month) involved evaluating the existing quality and safety control system. The second stage (8 months) focused on the introduction of all innovative measures – new sanitation products, improved equipment cleaning protocols, the use of probiotic supplements, and automated milk monitoring systems. Since these interventions were introduced simultaneously, it was not possible to clearly distinguish the individual effects of each measure. However, the effectiveness of the integrated approach was evaluated by comparing pre- and post-intervention results, particularly in terms of microbiological milk characteristics, animal productivity, and economic parameters. The third stage (5 months) consisted of assessing the effectiveness of the implemented changes by comparing physicochemical, microbiological, and economic indicators.

During the implementation of the dairy safety improvement programme, a comprehensive analysis of production, microbiological, and economic parameters was conducted. Primary data on bacterial contamination levels, the proportion of non-standard milk batches, and procurement prices were obtained through laboratory tests and the enterprise's production reports for the period 2024–2025. In particular, the microbiological characteristics of raw milk were determined in accordance with methodologies described by researchers investigating microbiological risks in dairy products (He et al., 2023; Vidic et al., 2020). To assess the economic feasibility of the introduced innovative approaches, an analysis was carried out of the costs associated with the dairy safety improvement programme. The results were compared with baseline data on average market procurement prices for milk, as published by the State Statistics Service of Ukraine (n.d.).

Control group and experimental design

This study was designed as a prospective field evaluation conducted on a commercial dairy farm and consisted of two nested components (Table 1). First, the sanitation/monitoring and process-management innovations were implemented at the facility level. Therefore, their effectiveness was assessed using a before-after comparison (baseline stage versus post-implementation stages) based on repeated sampling of milk and environmental control points throughout the production chain. Second, the probiotic feeding intervention was evaluated on an animal-level cohort of 30 lactating Holstein cows selected to be as homogeneous as possible (age, physiological condition, productivity and housing conditions). For this cohort, baseline measurements were recorded before probiotic inclusion and then re-evaluated during supplementation.

Because the sanitation protocol, detergents and online monitoring were introduced across the production facilities, it was not operationally feasible to maintain a parallel, non-intervention production line on the same farm. Accordingly, the facility-level outcomes (microbial load of milk, hygiene swab results at critical control points, and economic indicators) are interpreted as changes relative to the baseline stage, with seasonality and routine management documented during the full lactation cycle.

For the probiotic cohort, the total mixed ration was identical to that of the main herd (Table 2), with the only planned change being the addition of probiotics to the concentrate during feed mixing. The probiotic additives were ProBioFeed (*Bacillus subtilis*; 150–200 g per 1 tonne of feed; Germany) and LactoStim (*Lactobacillus plantarum*; 100 g per 1 tonne of feed; Denmark). The additives were dispensed through an automated dosing system to ensure consistent delivery. Milk quality (e.g., total microbial count and somatic cell count), health status and production parameters were recorded at baseline and during supplementation, with the key comparisons reported as within-cohort (pre vs post) changes.

The Holstein breed of dairy cows is widespread not only in Ukraine but also across other European countries. For this reason, Holstein cows served as a model for studying the factors influencing the quality and safety of large volumes of dairy production, as well as the potential for modifying these factors. Thus, the choice of Holsteins was based not only on their availability at the study site but also on scientific relevance and the capacity to obtain reliable results applicable to modern intensive dairy farming. The research covered a complete lactation cycle, enabling the monitoring of changes in productivity and

Table 2 Typical daily ration per head

Component	Quantity, kg/head/day	Notes
Maize silage	20	Primary energy source
Alfalfa silage	12.5	High protein content
Wheat straw	2	Fibre source
Concentrated feed mix	6.5	Contained cereal and protein components (barley, soybean, oilcake)
Feed chalk	0.1	Source of calcium
Sodium chloride	0.05	Electrolyte balance
Vitamin-mineral supplement (Switzerland)	0.1–0.12	Universal premix

Source: compiled by the authors

milk quality from the beginning to the end of lactation. The choice of this period made it possible to account for seasonal variations (summer–winter), which is particularly important for studying the microbiological indicators and stability of dairy products.

As part of the research, the feeding ration of the dairy herd was optimised by introducing a balanced programme tailored to the physiological needs of the Holstein breed. Feeding was carried out three times a day – at 06:00, 13:00, and 19:30 – according to a consistent schedule designed to minimise stress factors and stabilise digestion. The diet was based on high-quality ensiled feeds (maize and alfalfa silage), hay, straw, and concentrates composed of maize, barley, and soybean meal (Table 2).

The nutritional value of the ration per 1 kg of dry matter included 16.5% protein, 33% neutral detergent fibre, 24% starch, and 3.5% fat, with a total metabolisable energy of 11.2 MJ/kg. Probiotic supplements were incorporated directly into the concentrate during mixing, ensuring uniform distribution and dosing stability. The feeding programme also included a vitamin-mineral supplement formulated to meet the physiological requirements of dairy cows for macro- and micronutrients, as well as fat-soluble and water-soluble vitamins. The composition of the supplement included calcium (180 g/kg), phosphorus (90 g/kg), sodium (50 g/kg), and magnesium (20 g/kg) as the main macronutrients. The micronutrient content comprised zinc (3,000 mg/kg), manganese (2,200 mg/kg), copper (900 mg/kg), iodine (60 mg/kg), selenium (30 mg/kg), and cobalt (25 mg/kg). The vitamin component consisted of vitamin A (1,000,000 IU/kg), vitamin D_3 (200,000 IU/kg), vitamin E (4,000 mg/kg), vitamin B1 (90 mg/kg), vitamin B_{12} (2 mg/kg), and biotin (20 mg/kg). The supplement was administered as a premix incorporated into the total mixed ration at a dosage of 100–120 g per head per day, depending on the stage of lactation, physiological condition, and productivity of the animals. To optimise feeding, a rapid feed analysis based on infrared spectroscopy was employed, allowing more accurate calculation of daily rations with respect to protein-energy balance. Before being introduced into routine use, a 10-day adaptation period was carried out on the control group of 30 animals.

Ethical considerations

All procedures related to housing, feeding, sample collection, and interventions during the experiment were conducted in compliance with current standards of animal welfare, including the provisions of the European Convention for the Protection of Vertebrate Animals used for Experimental and Other Scientific Purposes (1986), as well as the enterprise's internal animal welfare guidelines. No cases were recorded during the study that indicated any deterioration in animal health as a result of the experimental procedures. Ethical approval for this study was granted by the Ethics Committee of Mykolaiv National Agrarian University, approval number 51.

Laboratory and equipment analysis

The quality of dairy products was assessed using modern laboratory equipment, including a Bentley FTS milk analyser (France), a Shimadzu UV-1800 spectrophotometer (Japan), an Agilent 7890B chromatograph (Netherlands), an Olympus CX43 microscope (Japan), a Metrohm 913 pH meter (Switzerland), a TC-80 thermostat (China), an OPn-8 centrifuge (Kyrgyzstan), and a PerkinElmer Analyst 800 atomic absorption spectrometer (USA). During the implementation of the innovative hygiene system, sanitising agents were employed to ensure effective cleaning and disinfection of equipment and production facilities (Table 3).

The alkaline and acid detergents (Ecolab Topax 66, Topax 91) were applied for the main Clean-in-Place (CIP) washing of milk pipelines, tanks, and milking equipment. These products were supplied by the official distributor, Ecolab Ukraine Limited Liability Company, which ensured their quality and compliance with European standards (European Committee for Standardization, 2019).

The study involved a comparison of three different approaches to the sanitation of milking equipment:

Table 3 List of sanitising agents used

Product name	Purpose	Supplier	Country
Ecolab Topax 66	Alkaline detergent	Ecolab Ukraine LLC	Germany/Ukraine
Ecolab Topax 91	Acid detergent	Ecolab Ukraine LLC	Germany/Ukraine
Diversey Suma Bac D10	Surface disinfection	Diversey Ukraine	Netherlands
Diversey Clax Sonril	Disinfection of dairy equipment	Diversey Ukraine	Netherlands
Henkel P3-oxonia	Tank disinfection	Henkel Ukraine	Germany
Philips UV lamps	Air sterilisation	Philips Ukraine	Netherlands

Source: compiled by the authors

traditional washing, CIP washing, and a combined washing system. Traditional washing involved the manual rinsing of milking equipment components using separate tanks, hoses, and brushes. CIP washing is an automated cleaning system in which cleaning solutions circulate through all elements of the milking equipment without the need for disassembly. A combined washing system was also employed, integrating both manual and automated cleaning methods. In this approach, the internal circuits of the milk pipeline were cleaned using the CIP system, while the external surfaces of equipment and tanks were cleaned manually. To enhance biosecurity within production facilities, ultraviolet lamps were used to sterilise the air, reducing the risk of secondary microbial contamination.

During the study, a standardised sanitation system for equipment was applied, which included an initial rinse with warm water at 35-45 °C, followed by circulation of an alkaline solution at 70 -80 °C. This was succeeded by an intermediate rinse, circulation of an acid solution, and a final rinse with mandatory disinfection. The procedure concluded with drying the equipment using sterile air. After implementing this procedure, a critical control point system was established, covering all key stages of the production process: milking equipment, milk pipelines, cooling tanks, milk reception points, and the pasteuriser. Clear microbiological contamination thresholds were set for each point.

For the physicochemical evaluation of milk quality, standardised methods were used to determine fat and protein content (Bentley FTS milk analyser), density, acidity, and freezing point (State Service of Ukraine on Food Safety and Consumer Protection, 2024). Microbiological indicators included the determination of total bacterial contamination by performing deep plating on nutrient media, followed by colony counting after incubation (30 °C ± 1 °C, 72 ± 3 h), as well as the quantification of somatic cell counts through fluorescent staining and laser-based flow cytometry. Identification of pathogenic microorganisms, including *Salmonella* spp., *Listeria monocytogenes*, and *Escherichia coli*, was also conducted (International Organization for Standardization, 2013). Safety assessment involved testing for mycotoxins and heavy metals. Residual antibiotics were detected using the disc-diffusion method, in which sterile paper discs were impregnated with milk samples and placed on agar inoculated with a sensitive test culture (*Bacillus stearothermophilus*). Particular attention was paid to the detection of aflatoxin M1 using high-performance liquid chromatography with fluorescent detection, as well as cadmium and lead, the most common contaminants in milk, according to ISO 14501:2021 "Clean-up by Immunoaffinity Chromatography and Determination by High-Performance Liquid Chromatography" (2021). For heavy metal analysis, milk samples were first treated with nitric acid (HNO_3) and hydrogen peroxide (H_2O_2). The digested samples were then introduced into a graphite furnace atomic absorption spectrometer. Cadmium and lead concentrations were measured at wavelengths of 228.8 nm (Cd) and 283.3 nm (Pb), respectively.

To support the study, an automated milk quality monitoring system, the Milkline Dairy Management System (DMS) (Italy), was employed. This system provided continuous monitoring and recording of milk quality, equipment condition, temperature regimes, and the effectiveness of sanitation throughout the entire production cycle, allowing real-time evaluation of both process hygiene and product quality. The DMS operated through several key components: milk analysis modules (optical sensors and infrared spectrophotometers), integrated temperature and conductivity sensors, software with data visualisation capabilities, and a cloud-based data storage system. Using sensors installed in the milk pipeline, hourly measurements were taken of milk temperature during milking, electrical conductivity, milk acidity, residual moisture and cleaning agent levels during sanitation, water temperature during equipment washing, and the timing and duration of each milking cycle. The data were transmitted to a centralised management interface, where they were processed and presented as graphs and tables, which were then used to generate automatic reports on observed trends. This allowed for the rapid detection of deviations, the prevention of animal health issues, and the precise regulation of temperature and washing regimes.

Automated milk quality monitoring system

As part of the economic assessment of the implemented innovations, a comprehensive analysis of costs and benefits was conducted, focusing on the modernisation of technological equipment, including the installation of automated systems for monitoring the temperature during milking equipment cleaning and milk storage tanks. The methodology involved comparing direct production costs before and after the technological upgrades, calculating monthly savings for key items (electricity, cleaning agents, labour, and product losses), and determining the payback period. The total capital investment for implementing the new systems amounted to UAH 169,400, covering the purchase of equipment (automated cleaning control systems, temperature sensors, management modules), installation, personnel training, and integration with existing infrastructure. Monthly savings were calculated using formula (1):

$$E = E_1 + E_2 + E_3 + E_4 \tag{1}$$

where E_1 is the savings on electricity, E_2 is the savings on cleaning agents, E_3 is the reduced labour costs, E_4 is the reduced losses due to decreased defective products, and E is the total monthly savings.

The payback period was calculated using formula (2):

$$T = \frac{C}{E}, \tag{2}$$

where T is the payback period and C is the capital investment.

The dynamics of milk sales were also compared with baseline average purchase prices published by the State Statistics Service of Ukraine (n.d.). In addition, the total increase in enterprise profit was calculated as a percentage, taking into account reduced veterinary costs and increased milk sales.

The study was conducted on a single, large-scale commercial farm, which may limit the generalizability of the findings to other production systems. The farm's advanced infrastructure, automated milking systems, and well-established veterinary and hygienic protocols may not be representative of smaller farms or those with fewer resources. For example, the successful integration of automated monitoring and probiotic supplementation at this large farm may be more difficult for smaller operations due to cost and technical challenges.

The specific genetic makeup of the Holstein cows, known for high productivity, also influenced the results. Other breeds or farms with different herd sizes may experience varying outcomes in terms of milk yield and health improvements. Additionally, while the study accounted for seasonal variations, findings may differ in regions with different climates, feed availability, or management practices. While these results are promising for large-scale operations, further research involving diverse farm types is needed to assess the applicability of these interventions in other settings. Therefore, the generalization of these findings should be approached with caution.

Statistical analysis

Statistical analyses were planned to reflect the two levels of intervention described in Table 1. For the animal-level probiotic cohort ($n=30$), baseline values were compared with measurements obtained during supplementation (Day 60) using paired tests (paired t-test for normally distributed variables or Wilcoxon signed-rank test when normality was not met) and repeated-measures linear mixed models with cow as a random effect. Fixed effects included time point (pre vs post), month/season and stage of lactation to partially account for temporal confounding. For facility-level outcomes (bulk milk microbiology, hygiene swab counts at critical control points, and economic indicators), the sanitation/monitoring and equipment upgrades were implemented farm-wide as a bundled programme. Therefore, their effectiveness was assessed using before-after comparisons and interrupted time-series regression on repeated monthly observations, including month indicators. Because several process-level interventions were introduced concurrently, their individual effects are not statistically identifiable (high collinearity), and the regression models were interpreted as estimating the combined effect of the integrated programme rather than isolated impacts of single measures. A significance level of $p < 0.05$ was applied. Calculations were performed using STATISTICA 10.0 and Microsoft Excel 2021.

Results

Effectiveness of sanitation methods and automated monitoring systems

Primarily, the study involved a staged assessment of milk quality, production process efficiency, and the safety of the final product. This process was accompanied by the implementation of innovative technologies aimed at enhancing safety and quality parameters. In particular, an automated critical control point monitoring system was applied, allowing continuous observation of the hygiene status of equipment and facilities. With traditional washing, cleaning solutions were prepared and applied manually, and the process was not automated, increasing the risks of human error and inconsistency in cleaning quality. This method is more suitable for small farms with limited technical resources. Consequently, CIP systems were also employed, providing stepwise cleaning (pre-rinse, main wash with detergent, rinse) with precisely controlled temperature, time, and detergent concentration. Within the study, the CIP system achieved the highest results according to microbiological criteria, ensuring consistently high hygiene standards, which is particularly suitable for large-scale dairy operations. In the first stage, the effectiveness of different sanitation methods was compared. As shown in the diagram below, the combined CIP washing system achieved the highest level of bacterial removal (99%) (Fig. 1).

The combined approach also resulted in a reduction of sanitation time from 120 to 60 min and a decrease in cleaning agent consumption from 240 to 150 L per cycle (Fig. 2). This approach allowed the process to be adapted to the specific production conditions, optimising resource use while maintaining a high level of hygiene. Differences between washing systems in terms of automation, consistency of cleaning parameters, water and detergent consumption, and energy expenditure enabled the achievement of an optimal balance between cleaning quality and operational costs.

The combined CIP system effectively removed bacterial contamination from the internal surfaces of equipment

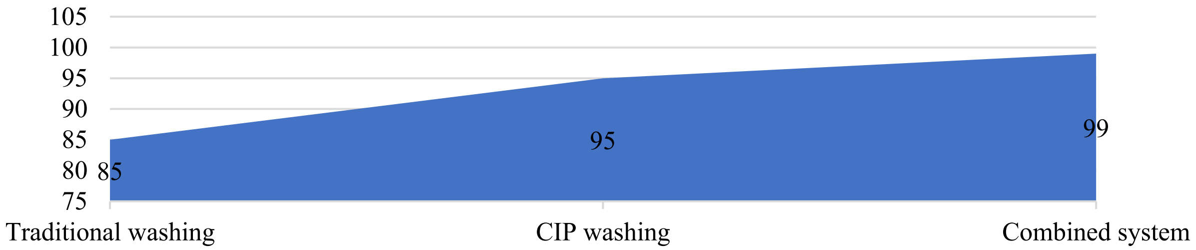


Fig. 1 Comparison of sanitation method effectiveness. Source: compiled by the authors

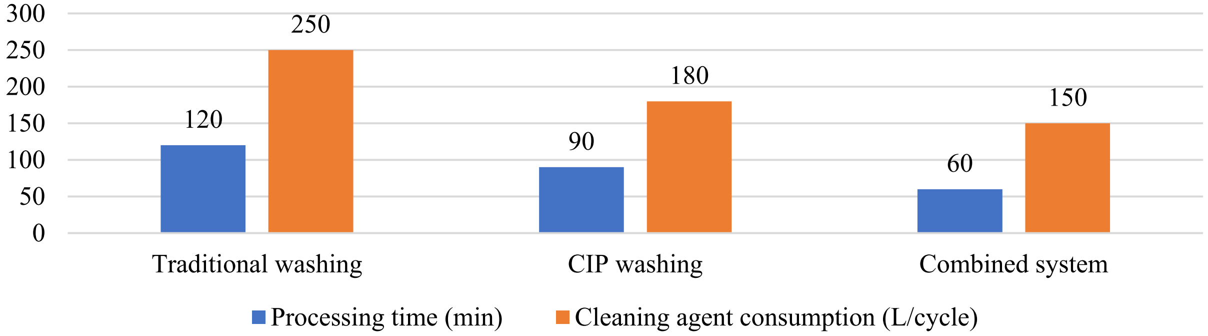


Fig. 2 Reduction of resource use with the combined CIP washing system

while simultaneously reducing detergent use. In the first stage, a pre-rinse with warm water was performed to remove residual milk from surfaces. The second stage involved the circulation of an alkaline cleaning solution to break down protein-fat residues and eliminate vegetative forms of microorganisms. An intermediate rinse removed any remaining alkaline residues to prevent chemical reactions with subsequent reagents. This was followed by the circulation of an acidic solution, which aided in biofilm dehydration, prevented the formation of milkstone, and enhanced disinfection efficacy. The final rinse with clean water and treatment with a certified disinfectant completed the cleaning process. In the last stage, the equipment was dried with sterile air, minimising the risk of recontamination. The advantage of the combined system was its high reproducibility of results.

Improvements in milk quality and animal health

However, certain challenges were noted, including the need for precise calibration of temperature and pressure parameters, as well as the high maintenance requirements for the system's automated components, particularly during the early stages of implementation. As a result of introducing this system, critical microbial contamination limits were consistently maintained across all key stages – from the milking equipment to the pasteuriser – confirmed by bacteriological monitoring results (Fig. 3).

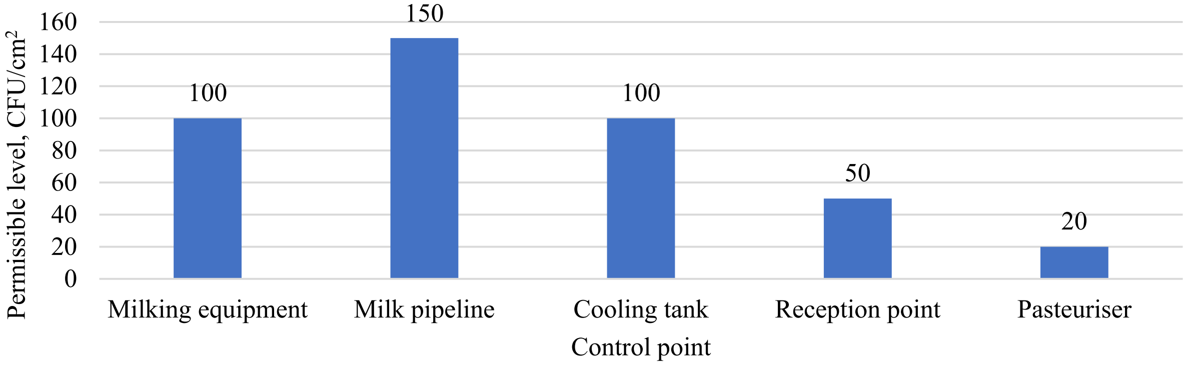


Fig. 3 Critical microbial contamination limits for control points. Source: compiled by the authors based on ISO 4833–1:2013 "Horizontal Method for the Enumeration of Microorganisms. Part 1: Colony Count at 30 Degrees C by the Pour Plate Technique" (2013)

The installation of an automated monitoring system allowed microbial control at different frequencies across the production process. For milking equipment, measurements were taken twice daily (limit: 100 CFU/cm^2). For the milk pipeline (limit: 150 CFU/cm^2) and cooling tank (limit: 100 CFU/cm^2), monitoring occurred once daily. At the reception point, measurements were recorded twice daily (limit: 50 CFU/cm^2), and in the pasteuriser, three times daily (limit: 20 CFU/cm^2). This approach also permits adjustment of monitoring frequency according to specific technological requirements. Analysis of surface swab samples following sanitation indicated improved microbial cleanliness of equipment after the implementation of the new sanitation system (Table 4).

Sensors were also used to monitor cleaning quality, enabling rapid identification of deviations from established hygiene standards. A significant reduction in bacterial contamination was observed following the implementation of the updated cleaning regime, improvements in the sanitation of the milking parlour, and the use of automated monitoring. Somatic cell counts also decreased, indicating a reduction in subclinical mastitis (Table 5).

Positive changes were observed within the first months of introducing the innovative approaches, as illustrated in the consolidated monthly microbiological monitoring chart, showing trends of reduced bacterial contamination and lower somatic cell counts in the samples (Fig. 4).

These data confirmed an improvement in hygiene standards at the enterprise and the effectiveness of the implemented sanitation procedures.

Economic impact and cost efficiency

Additionally, the herd's feeding programme was reviewed. By enriching the feed with a vitamin-mineral premix and functional additives, its energy and protein value were improved, while the inclusion of the probiotics *Bacillus subtilis* and *Lactobacillus plantarum* enhanced feed digestibility and strengthened the animals' immune systems. Following dietary adjustments, overall animal health improved, and the incidence of digestive disorders decreased. This was reflected in increased milk yields, reduced feed consumption per unit of output, and improved milk quality parameters (Table 6).

The use of probiotic supplements not only improved the herd's sanitary status but also significantly enhanced the quality and safety of the final dairy products. Analysis of the raw milk's physicochemical composition before implementing the innovations indicated an average fat content of 3.82%, protein 3.2%, and acidity 18.5°T. Following the introduction of the new approaches, including feed optimisation and automated milking, these quality parameters improved (Table 7).

The observed increase in milk fat and protein is consistent with the physiological effects expected from the

Table 4 Monitoring of equipment hygiene before and after the implementation of the new sanitation system

Control point	Indicator	Critical value (standard)	Before implementation, CFU/cm^2	After implementation, CFU/cm^2	Absolute change	% change	Cohen's d*
Milking equipment	Total microbial contamination	≤ 100	240 ± 20	85 ± 10	−155	−64.6%	−9.69
Milk pipeline	Total microbial contamination	≤ 150	180 ± 15	70 ± 12	−110	−61.1%	−8.01
Cooling tanks	Total microbial contamination	≤ 50	95 ± 10	35 ± 5	−60	−63.2%	−7.16
Pasteuriser	Total microbial contamination	≤ 20	80 ± 8	25 ± 4	−55	−68.8%	−8.20
Milk reception point	Presence of *Escherichia coli*	Absence	Detected in 1 of 10 samples	Not detected	–	–	–
Surfaces after CIP washing	Total microbial contamination	≤ 100	160 ± 18	60 ± 8	−100	−62.5%	−7.11

Source: compiled by the authors

Table 5 Microbiological indicators of raw milk

Indicator	Before implementation	After implementation	Absolute change	% change	Cohen's d*	*p*-value	Reference value
Total microbial count, CFU/mL	$(4.4 \pm 0.7) \times 10^5$	$(2.8 \pm 0.5) \times 10^5$	-1.6×10^5	−36.4%	−2.65	< 0.001	$\leq 3 \times 10^5$
Somatic cells, thousands/mL	420 ± 25	305 ± 20	−115	−27.4%	−5.06	< 0.001	≤ 400,000/mL
Detection of *E. coli*, % of samples	4%	0%	−4 pp	–	–	–	0% in a 25 mL sample
Detection of *S. aureus*, % of samples	3%	1%	−2 pp	–	–	–	< 1% or not detected in 25 mL

Source: compiled by the authors

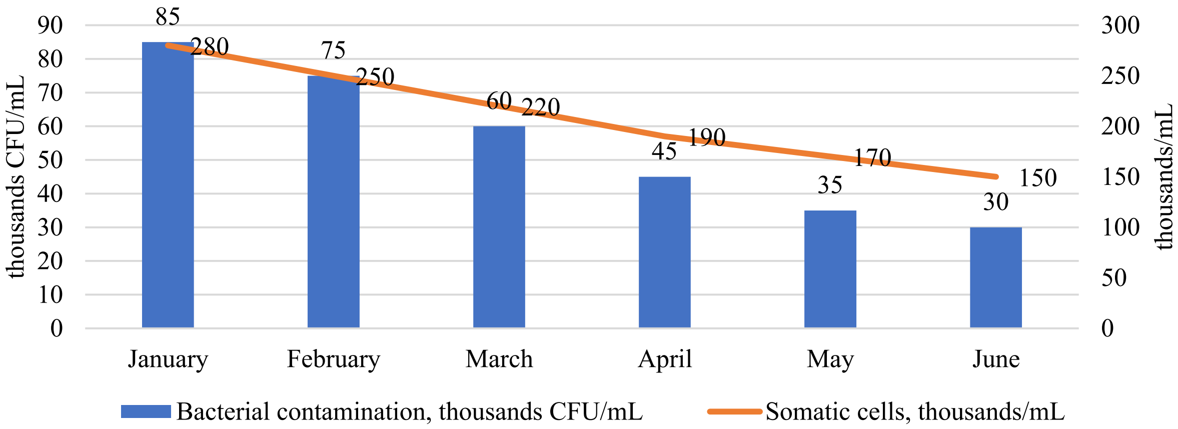


Fig. 4 Dynamics of microbiological indicators in raw milk from January to June 2024. Source: compiled by the authors

Table 6 Effect of probiotic supplements

Indicator	Before supplementation	After 60 days of supplementation	Change
Average somatic cell count, thousands/mL	390	210	−46%
Incidence of subclinical mastitis, %	12.5%	4.3%	−65.6%
Milk yield per cow, kg/day	22.4	24.9	+ 11.2%
Frequency of diarrhoea in young stock, %	18%	6%	−66.7%

Source: compiled by the authors

Table 7 Changes in the physicochemical characteristics of raw milk (mean ± standard deviation)

Indicator	Before implementation	After implementation	Δ (After–Before)	% change	Cohen's d*	*p*-value
Fat, %	3.82 ± 0.12	3.95 ± 0.1	+ 0.13	+ 3.4%	+ 1.18	< 0.01
Protein, %	3.2 ± 0.08	3.35 ± 0.07	+ 0.15	+ 4.7%	+ 2.00	< 0.01
Acidity, °T	18.5 ± 1.1	17.2 ± 0.9	−1.3	−7.0%	−1.29	< 0.05
Density, kg/m^3	1,028 ± 2	1,031 ± 1	+ 3	+ 0.29%	+ 1.90	< 0.01
Freezing point, °C	−0.534 ± 0.004	−0.539 ± 0.003	−0.005	–	− 1.41	< 0.05

Source: compiled by the authors

integrated intervention rather than being a purely technical artefact of measurement. First, improved udder health (lower somatic cell count (SCC) and reduced subclinical mastitis) supports normal mammary secretory activity and is commonly associated with better preservation of milk components, because inflammation is linked to altered permeability, enzymatic activity, and increased proteolysis that can depress true protein/casein fractions. Second, ration optimisation combined with probiotic inclusion (*Bacillus subtilis*, *Lactobacillus plantarum*) plausibly improved rumen stability and nutrient conversion efficiency, increasing the availability of fermentation end-products and microbial protein flow that serve as precursors for milk fat synthesis and milk protein formation (He et al., 2023; Nalla et al., 2022). Third, improved sanitation and shorter, standardised cleaning cycles likely reduced the risk of microbial lipases/proteases entering the milk chain and degrading fat/protein during collection and early handling, thereby supporting compositional stability in addition to microbiological safety (Martin et al., 2023; Medjahdi et al., 2025). The improvement in physicochemical characteristics reflects the combined effects of (i) improved metabolic and immune status under ration optimisation and probiotics, which increases nutrient availability for mammary synthesis, and (ii) reduced subclinical udder inflammation (lower SCC), which supports stable milk component formation. In parallel, automated monitoring of temperature and sanitation parameters reduced process variability and the likelihood of secondary contamination and component degradation during milking and primary handling, improving the consistency of fat/protein values over time.

It is also important to note the positive trend in milk protein content, which directly influenced the subsequent quality of the final product (Fig. 5).

Following the modernisation of the quality control system, a reduction in mycotoxin residues in the samples was recorded, along with a complete absence of antibiotics and a decrease in heavy metal concentrations to levels within acceptable limits (Table 8).

The implementation of the innovative measures resulted in a notable increase in the productivity of the milking herd, which directly impacted both milk yield and economic performance. As shown in Table 9, the average milk yield per cow increased by 12.1%, rising from 22.4 kg/day to 25.1 kg/day. This increase in milk yield also contributed to a 17% rise in revenue from milk sales, from 1,320 thousand UAH to 1,545 thousand UAH. Simultaneously, the expenditure on veterinary treatments decreased by nearly 40% (from 68 thousand UAH to 41 thousand UAH), indicating an improvement in animal health, likely due to the implemented feeding and management practices. These results demonstrate a clear economic benefit from the integrated measures, with increased milk production and reduced costs for animal healthcare.

The average milk yield per cow increased from 22.4 kg/day to 25.1 kg/day, reflecting improvements in feeding conditions and overall animal health. Given the difficulties Ukrainian milk producers faced in 2024–2025 due to the energy crisis and other economic challenges – in contrast to EU countries, where production costs remained stable thanks to state support – the economic component of the study focused on adapting existing mechanisms to new conditions.

Given the economic challenges faced by Ukrainian dairy producers in 2024–2025, including increased energy costs and market volatility, the economic analysis focused on quantifying how the implemented innovations affected production costs, revenue structure, and overall profitability, thereby strengthening the competitiveness of the enterprise on both domestic and foreign markets.

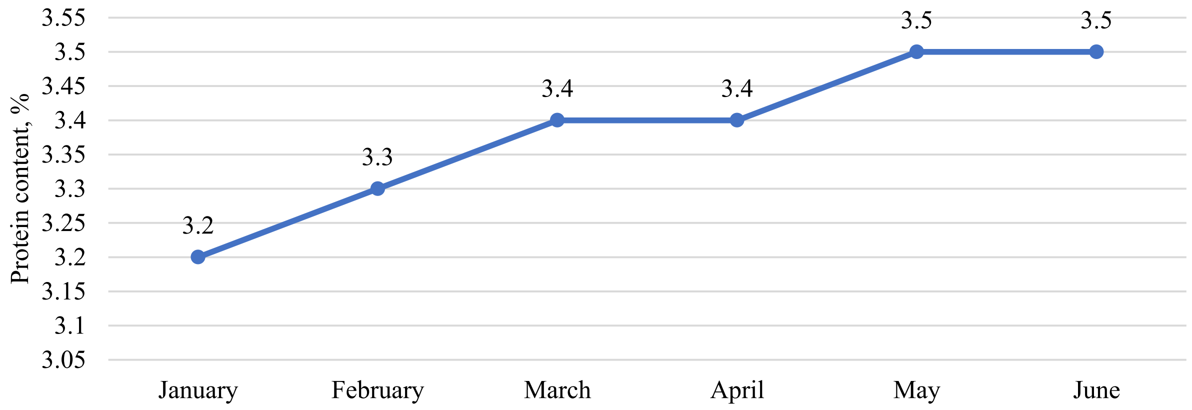


Fig. 5 Trend in milk protein content from January to June 2024. Source: compiled by the authors

Table 8 Milk safety indicators

Indicator	Before implementation	After implementation	*p*-value
Antibiotics, % positive samples	6%	0%	0%
Aflatoxin M1, µg/L	0.038 ± 0.002	0.022 ± 0.001	≤ 0.05
Lead, mg/kg	0.024 ± 0.003	0.012 ± 0.002	≤ 0.02
Cadmium, mg/kg	0.009 ± 0.001	0.005 ± 0.001	≤ 0.01

Source: compiled by the authors

Table 9 Economic indicators before and after the implementation of innovations

Indicator	Before implementation	After implementation	Change, %
Average milk yield per cow, kg/day	22.4	25.1	+ 12.1%
Revenue from milk sales, thousand UAH	1,320	1,545	+ 17%
Expenditure on treatment, thousand UAH	68	41	–39.7%

Source: compiled by the authors

Probiotic supplementation was associated with measurable improvements in herd health and productivity, reflected in a reduction in somatic cell counts and the incidence of subclinical mastitis, alongside an increase in average milk yield. These biological effects translated directly into economic benefits through lower veterinary expenditures and higher volumes of marketable milk.

Improved microbiological stability of raw milk enabled the enterprise to consistently meet extra-grade quality requirements, allowing sales to processors operating under international standards. As a result, the average purchase price of milk increased by 8% compared with the baseline period, contributing to higher revenue per unit of output.

The economic efficiency of investments in technological modernisation was assessed by comparing monthly operating costs before and after the introduction of automated systems for controlling temperature regimes during the cleaning of milking equipment and storage tanks. Precise temperature control reduced energy consumption for heating by approximately 10%, corresponding to monthly savings of UAH 5,100 (E_1). Automated dosing of cleaning agents decreased their consumption, generating additional savings of UAH 3,600 per month (E_2). Process automation also reduced labour requirements and equipment downtime, lowering personnel costs by UAH 2,900 per month (E_3). Furthermore, improved cleaning efficiency reduced product losses associated with incomplete sanitation, yielding savings of UAH 3,800 per month (E_4).

Total monthly savings (E) were calculated as the sum of these components:

$$\begin{aligned} E &= E_1 + E_2 + E_3 + E_4 \\ &= 5,100 + 3,600 + 2,900 + 3,800 \\ &= 15,400\ UAH. \end{aligned}$$

Thus, the total monthly cost reduction attributable to the technological modernisation amounted to approximately UAH 15,400, indicating a high level of operational efficiency. In relative terms, expenditure on cleaning agents declined by 15%, while electricity costs decreased by 10% (Fig. 6).

The capital investment required for implementing the automated monitoring and cleaning control systems totalled UAH 169,400. The payback period (T) was calculated using formula (2):

$$T = \frac{C}{E} = \frac{169,400}{15,400} \approx 11\ months.$$

Accordingly, the investment was recovered within approximately 11 months, primarily due to reduced energy consumption, lower expenditure on disinfectants, decreased labour costs, and reduced product losses. In parallel, probiotic supplementation increased average milk yield per cow by 12.1%, equivalent to an additional 150–170 L per cow per production cycle, which offset the cost of feed additives. Combined with reduced veterinary expenses and higher milk sales revenue, these factors resulted in an overall profit increase of 23.4% compared with the baseline period.

In Table 10, a comparison with the national average further emphasizes the success of the improvements. The farm's yield per cow reached 13,000 kg/year, which

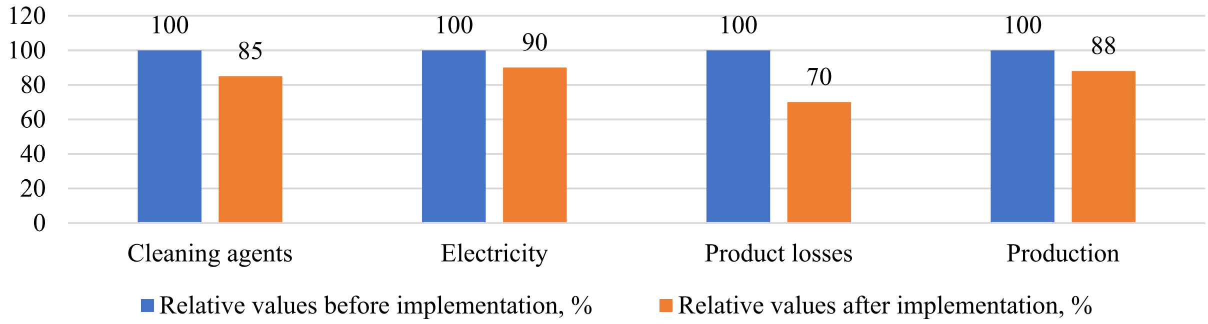


Fig. 6 Changes in associated costs before and after implementing innovations. Source: compiled by the authors

Table 10 Farm performance after implementation compared with the national average

Indicator	Farm data (after)	State Statistics Service data	Deviation
Purchase price, UAH/L	13,84	13,84	–
Yield per cow, kg/year	13,000	6,100 (national average)	+6900
Share of rejected milk	< 1%	5%–6% (national average)	–4%–5%

Source: compiled by the authors based on data from the State Statistics Service of Ukraine (n.d.)

is significantly higher than the national average of 6,100 kg/year, representing an increase of 6,900 kg per cow per year. Moreover, the share of rejected milk, which is a key indicator of product quality, was reduced to less than 1%, far below the national average of 5%–6%. This reduction in non-standard milk, coupled with the improved milk yield, highlights the enhanced overall performance and quality of the farm's dairy production, aligning with European efficiency standards and offering a competitive advantage in the market.

To evaluate the individual impact of each intervention on the observed outcomes, a detailed analysis of the contributions of probiotics, improved sanitation, equipment upgrades, and feeding adjustments was conducted. The introduction of probiotic supplements (ProBioFeed and LactoStim) resulted in a 47% reduction in bacterial contamination of raw milk, with total microbial counts decreasing from $(4.4 \pm 0.7) \times 10^5$ CFU/mL to $(2.8 \pm 0.5) \times 10^5$ CFU/mL. The detection rate of E. coli in the samples also dropped from 4 to 0% after supplementation. Probiotic supplementation further contributed to an 11.2% increase in average milk yield per cow, from 22.4 kg/day to 24.9 kg/day.

The implementation of improved sanitation systems, including the combined CIP cleaning method, resulted in a 99% reduction in bacterial contamination. For instance, microbial contamination on milking equipment was reduced from 240 ± 20 CFU/cm^2 to 85 ± 10 CFU/cm^2, and the contamination in the milk pipeline decreased from 180 ± 15 CFU/cm^2 to 70 ± 12 CFU/cm^2. These sanitation measures also contributed to a 31% reduction in the proportion of non-standard milk batches, allowing more milk to be sold as extra-grade. This led to an 8% increase in the average purchase price of milk.

Upgrades to equipment, including the installation of automated milk monitoring systems, improved overall process efficiency by reducing product losses due to inadequate cleaning and optimizing temperature control during milk storage and cleaning. This resulted in a 10% reduction in energy consumption for heating, yielding monthly savings of approximately UAH 5,100. The automation also led to a reduction in labour costs, saving UAH 2,900 per month, which contributed to overall operational cost savings.

Feeding adjustments, including the incorporation of a vitamin-mineral premix and functional additives, led to a 65.6% reduction in the incidence of subclinical mastitis (from 12.5% to 4.3%) and a 46% reduction in somatic cell counts. These changes were also associated with a 12.1% increase in milk yield per cow, translating to an additional 150–170 L of milk per cow per lactation cycle.

By quantifying the contributions of each intervention, it is clear that the combined effect of probiotics, improved sanitation, equipment upgrades, and feeding adjustments significantly improved both milk quality and animal productivity. These interventions also led to substantial economic gains, including a 23.4% increase in profit, demonstrating the effectiveness of the integrated approach.

Because multiple interventions were applied in parallel, attribution of the observed changes to any single measure requires caution. The sanitation protocol, detergents, equipment modernisation and automated Milkline DMS monitoring were rolled out farm-wide as a single package, so their individual effects on facility-level outcomes cannot be separated empirically from one another or from broader time trends.

Accordingly, improvements in environmental hygiene (Table 4) and in bulk milk microbiological quality (Table 5) are reported as effects of the integrated process-level programme (hygiene upgrades plus real-time monitoring), rather than as isolated impacts of a single component. These indicators are closely linked to equipment cleanliness and process control, but they remain jointly determined by the bundled implementation.

The probiotic feeding intervention was evaluated on a defined cohort of 30 Holstein cows using within-animal (pre vs post) comparisons (Table 6), which provides the strongest basis in this study for interpreting animal-level changes during supplementation. Nevertheless, the cohort was embedded within the same farm-wide roll-out, and residual confounding (e.g., reduced environmental bacterial pressure, seasonal effects, and concurrent management adjustments) cannot be fully excluded even after statistical adjustment. Therefore, the Results present combined programme effects for facility outcomes and within-cohort changes for the probiotic group, while the Discussion outlines the implications of this non-factorial design.

The study confirmed that the introduction of biotechnological methods and technological modernisation is not only effective in improving the quality and safety of dairy products but also economically justified, even within a single production cycle. While continuous monitoring and the identification of critical control points are well-established concepts in dairy production, the novelty of this study lies in the implementation of a fully integrated, automated system for real-time milk quality monitoring, tailored to the specific needs of large-scale dairy operations. Unlike traditional monitoring methods, which often rely on manual checks or periodic sampling, the system in this study continuously tracks key parameters such as milk temperature, acidity, conductivity, and sanitation levels during milking, storage, and processing. This approach not only enhances the precision of monitoring but also allows for immediate corrective actions based on real-time data, thus reducing the risk of contamination and improving overall process stability.

The integration of this monitoring system with automated cleaning processes and the use of predictive analytics to forecast potential quality issues represents a significant advancement over existing practices. The system also provides a comprehensive database for long-term trend analysis, which enables continuous optimization of production parameters. This combination of automation, data integration, and predictive analytics is what distinguishes this study from prior work, adding both practical and scientific value to the dairy production process.

While the concept of continuous monitoring is not new, the innovative application of this system within the context of this study – considering the specific technological and logistical challenges of large-scale dairy operations – adds a unique contribution to the field, advancing the efficiency and sustainability of dairy production.

Discussion

The results demonstrate the effectiveness of the implemented innovations in enhancing the quality and safety of dairy products, aligning with global trends in the dairy industry. Particular attention was paid to reducing the bacterial load in milk, which aligns with the observations of other authors regarding the importance of microbiological control of raw milk and the consideration of potential contamination risks to ensure the quality of raw material for subsequent processing (Martin et al., 2023; Bal-Prylypko et al., 2024; Medjahdi et al., 2025).

Vidic et al. (2020) also emphasised the hazard posed by *Bacillus cereus* in dairy products, making the reduction of microbial load in this study of practical significance for food safety. Additionally, researchers from India, including Nalla et al. (2022), analysed the impact of probiotics on the growth, lactation, and health of dairy cow breeds. They reported a direct relationship between the inclusion of probiotics in the diet and the animals' subsequent resistance to infections. These findings are fully consistent with the results of the present study, where enriching the diet of lactating cows with *Bacillus subtilis* and *Lactobacillus plantarum* contributed to a reduction in bacterial contamination in their milk. Conversely, the review by Widyastuti et al. (2021), El Jeni et al. (2024) highlights limitations in probiotic use due to the insufficiently studied mechanisms of their action. However, as in the present research, they noted the positive effect of this approach on the profitability of dairy enterprises. The beneficial impact of the probiotics applied in this study was associated with their ability to suppress the growth of opportunistic pathogenic microflora, corroborating the findings of previous authors. Thus, the preventive use of probiotics was significant not only for productivity but also for ensuring microbiological safety. A similar perspective was expressed by He et al. (2023), who emphasised the importance of probiotics in preventing gastrointestinal diseases and enhancing immunity, correspond to the reduction in somatic cell counts observed in the experimental milk.

Although reproductive parameters (conception rate, days open, calving interval, services per conception) were not quantified as primary endpoints in this study, the direction of the health changes observed provides a clear biological justification for expecting improved reproductive resilience. Reduced subclinical mastitis, lower SCC, and reduced diarrhoea frequency indicate a lower systemic inflammatory burden and improved nutrient partitioning, which are widely recognised prerequisites for successful cyclicity and conception in high-producing dairy cows. In practical herd management, fewer inflammatory episodes and reduced antibiotic interventions also decrease the likelihood of reproductive disruptions linked to illness, treatment withdrawal periods, and stress. Therefore, while direct reproductive outcomes cannot be claimed from the present dataset, the observed improvements in udder and digestive health plausibly support improved reproductive performance under intensive systems and should be measured explicitly in follow-up studies.

Shahini et al. (2023) demonstrated that even plant-derived by-products (notably oilseed cake) can enhance the productivity of lactating animals, highlighting the relevance of innovative feeding solutions. In the context of this study, productivity gains were also achieved, albeit through the inclusion of probiotic supplements in the diet, which was accompanied by improvements in the physicochemical properties of milk and reduced costs. Unlike the findings reported by Shahini et al., the effectiveness of dietary innovations in this study was confirmed not only by increased milk yield but also by a reduction in microbial contamination, thereby further improving product quality.

Another important consideration concerned toxic residues arising from industrial contamination, which, according to Forcada et al. (2023), can accumulate in milk and affect consumer health. To address this issue, an online monitoring system was implemented, proving to be an effective tool for the early detection of deviations and for enhancing product control, enabling prompt responses to such challenges. The results of this study demonstrated the practical effectiveness of integrating digital technologies to ensure milk safety at the primary production level.

The application of genetically informed breeding strategies also represents a promising approach to improving the quality of agricultural products. A close association between genetic markers and milk yield indicates the potential to increase the profitability of enterprises where such strategies are implemented (Gritsienko et al., 2022, 2024; Qu, 2021). This approach not only enhances economic performance but also improves the technological compatibility of milk, particularly for specialised products with modified compositions, such as lactose-free dairy items, as reviewed by Li et al. (2023). Unlike the aforementioned study, the present research focused on microbiological stability and the reduction of product losses during primary processing. Consequently, further research could investigate more comprehensively the impact of selective breeding on the physicochemical characteristics of milk from Holstein cows. Regarding the genetic potential of animals, Djedović et al. (2023), Sokolenko and Farionik (2025), examined the productivity and longevity of Holstein cows under conditions in Serbia. Similar observations were made in this study – animals of this breed exhibited high sensitivity to feeding and management conditions, yet, when optimally provided for, they demonstrated stable milk production.

Equally important is the functional enrichment of milk, particularly to enhance its antioxidant properties. Stobiecka et al. (2022) emphasised the significance of biologically active components in dairy products as a means of promoting consumer health. In a comprehensive review, Hidayat et al. (2023) also highlighted the positive effect of milk on bone strength in children when incorporated into the diet. Additionally, Bu et al. (2021) and Rizzoli (2022) noted the broader health benefits of milk consumption, underscoring the relevance of improving the quality parameters of this product. Johansson et al. (2019), Li et al. (2023) highlighted the growing market for lactose-free milk, underscoring the need for technological advancements in raw milk processing.

Amid the rise of plant-based milk, traditional dairy products remain vital due to their safety, stability, and nutritional value. Biscotti et al. (2023), Khamzaeva et al. (2024) discussed the competition between animal and plant-based milk, stressing that the microbiological safety of animal milk ensures its continued importance in industrial applications. This study supports those findings, demonstrating that probiotic supplementation and improved cow management practices enhance the safety and quality of raw milk, allowing it to remain competitive. Finally, while Alsaedi et al. (2023) focused on energy-efficient milk pasteurization, this study achieved energy savings not through processing, but by optimising raw milk quality at the milking and transportation stages.

The economic aspect of this research aligns with the findings of Walsh et al. (2020), who, analysing a decade of experience in organic dairy farms in the USA, concluded that the introduction of technological innovations and adaptive management substantially enhanced the profitability of such enterprises. In the European context, similar trends were observed in the articles of Djedović et al. (2023) and Stobiecka et al. (2022), where shifts in consumer behaviour and the demand for high-quality products compelled producers to modernise approaches to milk processing, reduce losses, and optimise production processes. In particular, the experience of Slovakia was considered, where innovation in agriculture is regarded as a tool for reducing food losses and improving the efficiency of agricultural production (Kapsdorferova et al., 2023b; Mazur & Dyshliuk, 2025).

Malik et al. (2025) consider the traceability of dairy products to be a key factor in creating sustainable and reliable supply chains, arguing that effective systems are based on transparency, accountability, and reliable data throughout the entire “farm-to-table” process. In their discussion, digital traceability is not limited to end-point certification; it depends on the continuous recording of operational events (hygiene, temperature, processing, and quality deviations) that can be verified and audited to build consumer confidence and regulatory compliance, particularly with regard to risks related to adulteration, contamination, and quality standards. This perspective directly complements this study, in which critical control points were monitored at high frequency and the Milkline DMS system generated structured, time-stamped data on sanitation parameters and milk quality dynamics. From a practical standpoint, these data sets constitute “traceability-ready” streams of evidence that can be extended beyond the farm (packaging, transportation, and processing) to support rapid root cause analysis and targeted product recall decisions in the event of deviations.

At the same time, Malik et al. (2025) emphasize that the implementation of traceability is often limited by implementation costs, organizational resistance to change, and ongoing data management/privacy issues – barriers that are particularly important for producers operating in volatile markets. The economic results of this study (reduced losses, lower operating costs, and a short payback period for automation investments) point to a realistic way to overcome the “cost barrier,” demonstrating that digital monitoring can deliver immediate operating cost savings and lay the foundation for broader supply chain transparency. However, the transition from internal monitoring to full traceability will require collaboration (common data formats), clear rules for data access management, and cooperation between regulators, processors, technology providers, and farm management – an approach that is also emphasized by Malik et al. as necessary for sustainable implementation. In the future, aligning automated monitoring results with new traceability models could strengthen sustainability reporting and sustainability planning, supporting the long-term competitiveness of Ukrainian dairy companies in both domestic and export-oriented markets.

When comparing the results of this study with existing literature and practices in similar dairy farming contexts, several key observations emerge. The 12.1% increase in average milk yield per cow and the 17% rise in revenue from milk sales are consistent with findings from studies in both developed and developing dairy sectors that have implemented similar technological interventions, such as probiotic supplementation and advanced hygiene practices. However, the additional benefits of reducing veterinary treatment costs by nearly 40% are particularly noteworthy. This reduction in treatment expenses is more significant than in many comparable studies, where health costs often remain a substantial burden despite improvements in milk production.

Further, the reduction in the proportion of non-standard milk batches to less than 1%, compared to the national average of 5%–6%, demonstrates the effectiveness of the integrated approach in improving milk quality. This finding aligns with international standards for dairy safety, where strict quality control and hygiene practices are critical for meeting both domestic and export market requirements. In this regard, the results not only confirm existing knowledge but also present a model for adapting these innovations to farms with limited resources, particularly in emerging markets like Ukraine. By aligning these findings with comparative studies in EU and other Eastern European dairy systems, it becomes clear that the integrated approach adopted in this study enhances both the productivity and sustainability of dairy operations, thus offering significant potential for replication in similar agricultural settings. Thus, the results obtained were compared with existing literature, allowing the conclusion that the proposed approach is effective within the current trends of the dairy industry, both in Ukraine and in the broader European context.

While the study provides valuable insights, there are limitations that should be considered when interpreting causal effects. First, the research was conducted on a single, large-scale farm with advanced infrastructure, which may limit generalisability to smaller or less-resourced operations. Second, most process-level interventions (sanitation products and protocols, combined CIP cleaning, equipment upgrades and automated monitoring) were introduced together as a bundled programme. In statistical terms, the intervention indicators are time-locked and highly collinear, so multivariable regression cannot reliably estimate separate coefficients for each component, any attempt to do so would yield unstable, non-identifiable estimates. For this reason, facility-level outcomes are interpreted as changes associated with the integrated programme as a whole (before-after and interrupted time-series analyses), not as isolated effects of individual measures. The probiotic cohort provides partial isolation via within-cow comparisons. However, because it was embedded in the same farm-wide roll-out, residual confounding by seasonality, lactation stage and concurrent hygiene improvements cannot be fully excluded, even when adjusting for time and lactation variables in mixed models. Future studies should use designs that enable attribution, such as a factorial trial, a staggered (step-wedge) implementation, or inclusion of an external comparator farm to support difference-in-differences or hierarchical mixed-effects analyses.

During the implementation of innovative approaches, several challenges were encountered that required prompt responses and adjustments to certain organisational decisions. Insufficient staff familiarity with the technique for incorporating probiotics into the feeding system at the initial stage led to uneven dosing, which was reflected in fluctuations in the milk's microbiological indicators. This issue was resolved through staff training seminars and the introduction of visual instructions for mixing the supplements with feed. During the deployment of monitoring systems, part of the existing equipment proved incompatible with modern data transmission protocols. To ensure integration, the milking unit underwent technical upgrades, including the installation of a Bentley FTS analyser with local network support and automatic result upload to the enterprise database. Standardising the conditions for sample collection for laboratory testing also proved crucial. Initially, deviations were observed due to sample heterogeneity, affecting the reliability of the results. This was addressed by introducing a standardised sampling protocol, specifying precise timing, containers, and transport conditions for samples to the laboratory.

Conclusions

The study demonstrated that the implementation of innovative approaches to ensuring the safety and quality of dairy products, specifically, the use of an automated system for monitoring the physicochemical parameters of milk and the inclusion of probiotic feed additives (*Bacillus subtilis* and *Lactobacillus plantarum*), had a positive impact on the hygienic standards of production, the microbiological quality of raw milk, and the economic performance of the farm. The introduction of these innovations led to a series of beneficial changes, confirming the effectiveness of the adopted strategy. In particular, the somatic cell count in milk decreased by an average of 46% following the addition of probiotics to the diet, indicating an improvement in udder health and a reduction in inflammatory processes. Simultaneously, a reduction in bacterial contamination was observed, substantially lowering the proportion of milk rejected on microbiological grounds. In the monitored cows, the incidence of subclinical mastitis decreased from 12.5% to 4.3% during the probiotic supplementation period (Table 6), supporting improved udder health and overall herd resilience. Milk yields increased by 12.1% compared with the initial observation period, contributing to higher volumes of marketable dairy products. Consequently, farm revenue rose by 17%, driven by improved productivity and a reduction in losses associated with the rejection of raw milk. The findings support the feasibility of integrated probiotic and hygiene/monitoring interventions to improve milk safety and economic efficiency.

Future studies should focus on long-term evaluations across different farm types to assess the sustainability of observed improvements and identify optimal probiotic protocols for cattle diets. Research should also explore the interactions between the gastrointestinal microbiota, milk composition, and quality characteristics when using functional feed additives. Additionally, there is potential for developing industry standards for automated quality control systems and functional feed additives to further improve animal health, product safety, and market value.

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None.

Authors' contributions

Serhii Luhovyi: Conceptualization, Investigation, Writing—Original Draft. Tetiana Pidpala: Supervision, Resources, Writing—Review & Editing. Alla Bondar: Methodology, Writing—Review & Editing, Conceptualization. Mykhailo Tymofiiv: Project administration, Writing—Review & Editing, Investigation.

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Data availability

The authors confirm that the data supporting the findings of this study are available in the article.

Declarations

Ethics approval and consent to participate

All procedures performed in the study were in accordance with the ethical standards of the institutional research committee and with EU Directive 2010/63/EU for animal experiments. Ethical approval for this study was granted by the Ethics Committee of Mykolaiv National Agrarian University, approval number 51.

Consent for publication

The study was conducted without human participation. Informed consent is not required.

Competing interests

The authors declare no competing interests.

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