



Use of innovative technologies to extend the shelf life of dairy products

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Abstract. The aim of the study was to provide a comprehensive assessment of the impact of innovative technologies on the processing and treatment of dairy products in order to extend their shelf life. A comparative analysis of non-thermal methods revealed that high-pressure processing (600 MPa, 15 minutes) and pulsed electric fields (35 kV/cm, 1,000 Hz) were the most effective in inactivating microorganisms, reducing their overall count by 4.2 and 3.8 log CFU/cm³, respectively. Non-thermal techniques showed less impact on the nutritional composition of milk compared to traditional pasteurisation, preserving up to 91.8% of vitamin C and 97.2% of whey proteins. The best organoleptic properties were observed in samples treated with high-pressure processing and pulsed electric fields, scoring 4.9 out of 5 on a 5-point scale. It was also found that ultrasound treatment accelerated

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yoghurt fermentation by 28%-32%, high pressure shortened cheese ripening time by 30%-35%, and ultrafiltration increased the yield of acid-set cheese by 15%-18%. Among antimicrobial packaging materials, the highest activity was demonstrated by films containing silver nanoparticles (1.5%). A synergistic effect was observed when combining non-thermal processing methods with innovative packaging materials, enabling the extension of milk's shelf life to 35 days at a temperature of $4 \pm 1^\circ\text{C}$. Intelligent packaging systems with pH-sensitive indicators were developed for monitoring product freshness. To investigate the synergistic effect of combined treatments, a factorial experimental design was employed with the calculation of synergy coefficients. An analysis of nanoparticle migration from packaging materials showed that their concentration remained within permissible limits when recommended storage conditions were observed. Mathematical models were developed to predict milk shelf life based on processing and packaging parameters. An economic evaluation of the proposed technological solutions demonstrated their competitiveness in comparison with traditional methods, particularly in the production of premium-segment products

Keywords: non-thermal processing; high pressure; pulsed electric field; antimicrobial packaging; nanoparticles; intelligent packaging systems

Introduction

Dairy products constitute an important component of the human diet due to their high nutritional value and the bioavailability of their nutrients. However, these products are characterised by a limited shelf life owing to their microbiological vulnerability and susceptibility to oxidative processes. This issue highlights the need for the development and implementation of innovative processing technologies capable of extending the shelf life of dairy products without adversely affecting their organoleptic and nutritional properties. Traditional preservation methods, such as thermal pasteurisation and sterilisation, do not always provide an optimal balance between product safety and the retention of quality attributes. In particular, high-temperature processing often results in protein denaturation, vitamin loss, and a deterioration in taste.

Significant contributions to research on dairy quality preservation technologies have been made by V. Chiozzi *et al.* (2022), who conducted a comparative analysis of thermal and non-thermal food processing technologies. The authors noted that techniques such as ultrasound, ultraviolet (UV) irradiation, ozonation, and high hydrostatic pressure exhibit considerable potential for

microorganism inactivation in milk while exerting minimal impact on its sensory and nutritional characteristics. The researchers paid particular attention to the safety of applying these technologies in the dairy industry and their compliance with contemporary food safety standards. K.K. Dash *et al.* (2022) and E. Bancalari *et al.* (2020) investigated the effects of various thermal processing regimes on the quality and microbiological safety of milk and dairy products. The authors systematised data on the impact of both traditional and modified thermal treatments on the nutrient composition of milk and proposed alternative approaches aimed at minimising the adverse effects of heat treatment. These studies underscore the need to develop innovative technologies that ensure effective microorganism inactivation while preserving the biological value of dairy products.

In the field of intelligent packaging systems, significant contributions were made by A.M. Alizadeh *et al.* (2022) and P.P. Akhila *et al.* (2022), who analysed trends and opportunities for applying intelligent packaging to dairy products. The researchers categorised various types of active and intelligent packaging materials, including antimicrobial agents, oxygen scavengers,

moisture absorbers, as well as freshness sensors and temperature indicators. They also assessed the potential of these materials to extend the shelf life of different dairy product categories and their influence on consumer perception. S. Pandey *et al.* (2022) explored the application of bio-inspired active packaging materials to enhance the shelf life and safety of food products. The authors focused particularly on materials with antimicrobial properties based on natural compounds such as chitosan, essential oils, bacteriocins, and enzymes. They found that such materials are highly effective against a broad spectrum of microorganisms responsible for dairy spoilage, offering the added benefit of environmental safety in comparison with synthetic antimicrobial agents.

The barrier properties of packaging materials for dairy products were thoroughly examined by K. Sneha & A. Kumar (2022), who investigated the potential of nanoemulsions for enhancing packaging performance. The authors developed and characterised various types of nanoemulsions based on natural compounds with antimicrobial and antioxidant properties. Their findings showed that incorporating such nanoemulsions into packaging materials can significantly extend the shelf life of dairy products by enabling the controlled release of active components and creating an effective barrier against oxygen and moisture. The functional properties of dairy products under innovative processing technologies were studied by H. Sharma *et al.* (2023), who explored the impact of lactic acid bacteria and their metabolites on the techno-functional properties and health benefits of fermented dairy products. The authors found that using specific strains of lactic acid bacteria in combination with innovative processing techniques not only prolongs product shelf life but also enriches the products with bioactive compounds such as bioactive peptides, exopolysaccharides, and vitamins. Contemporary developments in automation and digitalisation in the food industry, including the dairy sector, were explored by S. Sharma *et al.* (2021). They analysed the potential of artificial intelligence and big

data analytics for optimising production processes, quality control, and predicting the shelf life of dairy products. The authors developed conceptual models of intelligent quality monitoring systems that integrate data from various sources – including in-pack sensors, storage conditions, and transport environments – to enable more accurate determination of actual shelf life under specific conditions. The environmental aspects of innovative technologies in the dairy industry were examined by W. Ahmed *et al.* (2022). The researchers conducted a comprehensive life cycle analysis of various packaging materials and processing technologies in terms of their environmental impact. They proposed strategies to reduce the ecological footprint of the dairy industry, including the use of biodegradable packaging materials, energy-efficient processing technologies, and the adoption of circular economy principles.

This study aimed to systematise and compare modern innovative processing and treatment technologies for dairy products with the objective of extending shelf life, while taking into account their effects on organoleptic, physicochemical, and microbiological quality indicators. To achieve this aim, it was essential to analyse the main factors limiting the shelf life of dairy products and to classify non-thermal and combined processing methods for both raw milk and finished dairy goods. It was also necessary to examine the effectiveness of various innovative technologies – including advanced packaging solutions – depending on the category of dairy product.

Materials and Methods

The study was conducted during 2023-2024 at the laboratory complex of the Department of Food Technology and Microbiology, Odesa National University of Technology. For the experimental part of the research, whole cow's milk was selected with a fat content of 3.2%, protein content of 3.0%, and total solids of 12.5%, in accordance with the requirements of DSTU ISO 707:2002 (2002). Special attention was paid to preventing potential contamination of samples during milk

collection. The microbiological indicators of the raw material met the regulatory standards: the number of mesophilic aerobic and facultative anaerobic microorganisms (MAFAM) did not exceed 1×10^5 CFU/cm³, and coliform bacteria and pathogenic microorganisms were not detected. For the comparative analysis of non-thermal processing methods, the following equipment was used: a UVC lamp unit (254 nm) with a radiation intensity of 30 mW/cm² for UV irradiation; a high-pressure system operating in the range of 300–600 MPa; a pulsed electric field generator with a field strength of 20–35 kV/cm and a frequency of 100–1,000 Hz; an ultrasonic generator operating at a frequency of 20 kHz and a power output of up to 1,000 W. To investigate antimicrobial packaging materials, samples of polyethylene film modified with silver, zinc oxide, and chitosan nanocomposites were used at concentrations of 0.5%, 1.0%, and 1.5%.

The impact of non-thermal processing methods on the technological properties of milk was studied under the following conditions: UV irradiation in a thin layer (4 mm) with exposure times of 10, 20, 30, and 40 seconds; high-pressure treatment at 300, 400, 500, and 600 MPa for 5, 10, and 15 minutes at a temperature of $15 \pm 2^\circ\text{C}$; pulsed electric field treatment with a field strength of 20–35 kV/cm, pulse duration of 1–4 μs , and frequency of 200–1,000 Hz in a continuous-flow system with a throughput of 1 L/min; ultrasound treatment at intensities of 30, 50, and 70 W/cm² for 5, 10, and 15 minutes at a temperature of $25 \pm 3^\circ\text{C}$. To assess structural changes in milk proteins caused by non-thermal methods, differential scanning calorimetry was employed. Microscopic analysis of milk structure was carried out using an optical microscope with a digital camera at magnifications of $\times 400$ and $\times 1,000$. The evaluation of the effectiveness of non-thermal methods in milk processing included the following: investigating the effect of ultrasound treatment (50 W/cm², 5 minutes) on yoghurt fermentation; applying high-pressure processing (500 MPa, 10 minutes) to accelerate cheese

ripening; using ultrafiltration in the production of acid-set cheese; employing pulsed electric field treatment of milk prior to drying. To assess the effectiveness of packaging materials, samples of milk treated using different methods were stored at a temperature of $4 \pm 1^\circ\text{C}$, with sampling carried out on days 1, 7, 14, 21, 28, and 35 of storage. The samples were analysed for microbiological parameters (total microbial count, psychrotrophs, and spore-forming bacteria), physicochemical indicators (pH, titratable acidity, viscosity, degree of fat oxidation, and vitamin content), and organoleptic characteristics using a 5-point scale. To investigate the synergistic effect of combining non-thermal processing methods with innovative packaging materials, factorial experimental design was applied, and synergy coefficients were calculated using the following formula 1:

$$S = \log\left(\frac{N_x}{N_a} \times N_b\right), \quad (1)$$

where N_x is the number of microorganisms after combined treatment; N_a and N_b are the number of microorganisms after individual treatments.

Energy efficiency of the studied technologies was evaluated by measuring electricity consumption (kWh/L) for each processing method. An economic assessment of the technological solutions was conducted, taking into account capital and operating costs, potential shelf life extension, and expansion of market reach. For statistical analysis of the results, analysis of variance was used. The significance of differences was assessed using Student's t-test at a confidence level of $p < 0.05$. All experiments were performed in five replicates.

Results

The study of non-thermal milk processing methods revealed significant differences in their effects on microbiological parameters and product shelf life. To enable an objective comparison of the effectiveness of different technologies, a comprehensive analysis was conducted, encompassing not only microbiological indicators but also technological aspects of applying these methods

in the processing of raw milk and the production of various dairy products. It was found that the highest level of microorganism inactivation in raw milk was achieved using high-pressure processing (600 MPa, 15 minutes) and pulsed electric field treatment (35 kV/cm, 1,000 Hz), which

extended the shelf life of milk to 21-28 days when stored at $4 \pm 1^\circ\text{C}$. A key consideration for the practical application of these technologies is their impact on subsequent processing stages and the quality characteristics of the final dairy products (Table 1).

Table 1. Effects of non-thermal processing methods on the technological properties of milk

Method of processing	Processing mode	Effect on protein fraction	Effect on technological properties	Energy consumption (kWh/L)
Control (untreated)	–	Native structure	Standard properties	–
Thermal pasteurisation	72°C, 15 s	Partial denaturation of whey proteins (18%-20%)	Improved cheese yield, reduction in vitamin content	0.12 ± 0.01
Thermal pasteurisation	90°C, 20 s	Significant denaturation of whey proteins (28%-30%)	Substantial improvement in water-holding capacity	0.18 ± 0.02
Ultraviolet irradiation	40 s	Minimal changes (2%-3%)	Preservation of native properties	0.04 ± 0.01
High-pressure processing	600 MPa, 15 min	Reversible denaturation (15%-18%)	Improved rennet coagulation, increased cheese yield	0.08 ± 0.01
Pulsed electric field	35 kV/cm, 1,000 Hz	Minimal changes (3%-5%)	Enhanced enzymatic processes	0.05 ± 0.01
Ultrasound treatment	70 W/cm ² , 15 min	Partial fragmentation (8%-10%)	Improved homogenisation, reduced fermentation time	0.09 ± 0.02

Note: values presented are means ± standard deviation (n = 5)

Source: compiled by the authors

As shown in Table 1, non-thermal processing methods offer significant advantages in preserving the native structure of milk proteins compared to thermal pasteurisation. Of particular interest are high-pressure processing and pulsed electric field treatment, which not only effectively inactivate microorganisms but also enhance the technological properties of milk for further processing. For instance, high-pressure processing (600 MPa, 15 minutes) leads to reversible denaturation of whey proteins, improving rennet coagulation and increasing cheese yield by 4%-6% compared to conventional thermal pasteurisation. Pulsed electric field treatment (35 kV/cm, 1,000 Hz) has minimal impact on the milk's protein fraction (changes of only 3%-5%), allowing the functional properties of the milk to be preserved almost at the level of raw milk,

while still ensuring a high degree of microbiological safety. Moreover, this technology has the lowest energy consumption among the methods studied (0.05 kWh/L), making it economically attractive for industrial implementation.

An analysis of the impact of different processing methods on the physicochemical parameters of milk showed that non-thermal techniques better preserve thermolabile components. The highest retention of vitamin C and whey proteins was observed following pulsed electric field treatment (91.8% and 96.5%, respectively) and ultraviolet irradiation (87.5% and 97.2%, respectively). These findings are particularly relevant for the production of functional dairy products with enhanced biological value. The study of structural changes in milk proteins using differential scanning calorimetry showed that high-pressure

processing (600 MPa, 15 minutes) induces conformational changes similar to those observed during mild thermal treatment (65°C, 30 minutes). However, unlike thermal processing, these changes are largely reversible, which explains the preservation of the proteins' functional properties. Pulsed electric field and ultraviolet irradiation caused only minimal structural alterations, with negligible effects on protein functionality.

Microscopic analysis of milk structure after different treatments revealed that ultrasound processing led to partial disintegration of fat globules and casein micelles, resulting in improved product homogeneity. This effect is particularly beneficial in the production of fermented dairy beverages and desserts, as it provides a more uniform texture and reduces the risk of whey separation. In addition to the impact on raw

materials, an important focus of the study was the effectiveness of combined technologies in extending the shelf life of finished dairy products. The combined use of non-thermal milk processing methods and innovative antimicrobial packaging materials demonstrated a synergistic effect. Milk treated with high-pressure processing and packaged in film containing silver nanoparticles (1.5%) maintained microbiological stability for up to 35 days, nearly twice as long as when each technology was applied individually. The study highlighted the broad potential of non-thermal technologies not only for raw material treatment but also at various stages of dairy product manufacturing. Experiments were conducted using non-thermal methods in the production of yoghurts, cheeses, and other dairy products, with the results presented in Table 2.

Table 2. Impact of innovative technologies on dairy product quality

Product	Technology	Technological effect	Impact on product quality	Economic effect
Yoghurt	Ultrasound treatment (50 W/cm ² , 5 min)	Fermentation time reduced by 28%-32%	Increased viscosity by 15%-20%, syneresis reduced by 25%-30%	Productivity increased by 23%
Yoghurt	High-pressure processing (400 MPa, 5 min)	Starter culture activity increased by 20%-25%	Improved texture, probiotic content increased by 1.2 log CFU/g	Shelf life extended by 14-18 days
Acid-set cheese	Ultrafiltration	Protein concentration increased 3.5-4 times	Product yield increased by 15%-18%, improved water-holding capacity	Production costs reduced by 12%-15%
Hard cheese	High-pressure processing (500 MPa, 10 min)	Ripening accelerated by 30%-35%	Intensified flavour compound formation, more uniform texture	Production cycle shortened by 20%-25%
Powdered milk	Pulsed electric field pre-drying	Dispersibility increased by 20%-25%	Improved solubility by 18%-20%, preservation of native protein properties	Energy consumption reduced by 10%-12%
Ice cream	Ultrasound treatment of mix (40 W/cm ² , 3 min)	Improved homogenisation, ice crystal size reduced by 40%-45%	Enhanced texture, heat stability increased by 15%-18%	Freezing time reduced by 22%-25%

Source: compiled by the authors

One of the most promising directions identified was the use of ultrasound treatment in yoghurt production. Treating the standardised milk mixture with ultrasound (50 W/cm², 5 minutes) before the addition of starter cultures reduced the fermentation time by 28%-32% compared to

traditional processing. This effect is attributed to ultrasonic cavitation, which causes partial disintegration of casein micelles and increases the availability of nutrients for the starter cultures. In addition, the final product exhibited increased viscosity (by 15%-20%) and reduced syneresis (by

25%-30%), contributing positively to its sensory properties and storage stability.

Studies on the effect of ultrasound treatment on yoghurt quality during storage showed that samples produced using this method maintained their sensory characteristics significantly longer than the control samples. After 21 days of storage at $4 \pm 1^\circ\text{C}$, yoghurts produced with ultrasound-treated milk showed 35%-40% lower syneresis and retained higher viscosity. Microbiological analysis revealed that the number of viable probiotic cultures in these samples was 0.8-1.0 log CFU/g higher compared to the control, confirming the positive effect of ultrasound treatment on probiotic viability. High-pressure processing has demonstrated considerable potential in the production of hard cheeses. Treatment during the ripening stage (500 MPa, 10 minutes) allowed the ripening process to be accelerated by 30%-35%, due to the intensification of proteolytic activity under high pressure. Flavour and aroma profile analysis showed that cheeses treated with high pressure had a richer taste and aroma compared to control samples at the same ripening stage. The economic benefit of this technology lies in the shortened production cycle and reduced maturation costs. A detailed study of the effects of high pressure on cheese proteolysis was carried out using chromatographic analysis of peptide profiles. It was found that high-pressure treatment (500 MPa, 10 minutes) led to the formation of low-molecular-weight peptides (under 5 kDa) in significantly greater quantities than in control samples after 60 days of ripening. These peptides play a key role in the development of flavour and aroma, and may also exhibit potential biological activity. Moreover, microstructural analysis of cheese after high-pressure treatment showed a more uniform distribution of moisture and fat within the cheese matrix, contributing to an improved texture in the final product.

Membrane technologies, particularly ultrafiltration, were investigated in the production of acid-set cheese. The use of ultrafiltration made it possible to increase the protein concentration

by 3.5 to 4 times without adversely affecting its functional properties. This led to a 15%-18% increase in product yield and improved water-holding capacity. An economic efficiency analysis showed that incorporating ultrafiltration into the production process reduced manufacturing costs by 12%-15%, owing to increased product yield and lower energy consumption. The ultrafiltration technique was also studied in combination with high-pressure processing for the production of functional cultured dairy products. It was found that pre-treatment of milk by ultrafiltration, followed by high-pressure treatment of the concentrate (400 MPa, 5 min) before the addition of starter cultures, resulted in a product with a higher protein content (8%-10%) and improved rheological properties. This approach is particularly promising for the manufacture of specialised dairy products for sports nutrition and geriatric diets, where a high protein content is a key factor. Pulsed electric field technology demonstrated high effectiveness in the production of powdered milk. Treatment of milk before drying (25 kV/cm, 500 Hz) enhanced dispersibility by 20%-25% and preserved the native properties of proteins. The resulting product exhibited improved solubility (by 18%-20%) and retained the functional properties of the proteins – an especially important characteristic in the production of infant formula and functional food products.

The study of the impact of pulsed electric field treatment on the milk drying process revealed that this technology can reduce energy consumption by 10%-12% by enhancing heat transfer and shortening drying time. Furthermore, microstructural analysis of the resulting milk powder showed that samples treated with pulsed electric field prior to drying exhibited a more porous particle structure, which accounted for their improved solubility. The functional properties of proteins, such as foaming capacity and emulsifying ability, were retained at 92%-95% of their original values, whereas these indicators dropped to 75%-80% in the control samples. Ultrasound-assisted re-emulsification

technology was explored in the production of butter and spreads. Treating cream with ultrasound (60 W/cm², 3 minutes) prior to churning resulted in a product with smaller water droplets (average diameter 2-3 µm compared to 5-7 µm in the control) and their more uniform distribution within the fat phase. This led to improved texture, enhanced thermal stability, and reduced tendency towards phase separation. Additionally, the product showed improved spreadability at low temperatures, broadening its potential applications. The microencapsulation technology using drum drying was investigated for the development of encapsulated probiotic cultures resistant to adverse environmental conditions. It was found that using sodium alginate and maltodextrin as coating materials significantly enhanced the survival of probiotic cultures under low pH conditions (pH 2.0, simulating gastric juice) by 2.5-3.0 log units compared to non-encapsulated cultures. This opens up new opportunities for the creation of functional dairy products with guaranteed delivery of probiotics to the consumer's intestines. As part of the study, intelligent packaging systems with pH-sensitive indicators based on anthocyanins were developed and tested for monitoring the freshness of dairy products. It was established that the indicator colour changed from blue to pink when the milk reached a critical acidity level (pH ≤ 6.0), allowing for visual assessment of product freshness without opening the package.

Experimental testing of the stability of the pH-sensitive indicators showed that they retained their activity throughout the entire shelf life of the dairy products (up to 45 days), provided that the recommended storage conditions were followed. An important feature of the developed indicators is their ability to respond specifically to changes caused by microbiological spoilage, without reacting to normal physico-chemical processes occurring in milk during storage. To enhance the effectiveness of quality control for dairy products, a concept for an integrated monitoring system was developed, combining intelligent packaging materials with automated

control systems. The system incorporates miniature sensors for pH, temperature, and gas composition, embedded into the packaging material; Radio Frequency Identification (RFID) tags for product identification and tracking; a central data collection and analysis platform using machine learning algorithms; and a mobile application for consumers, enabling them to obtain real-time information about product status by scanning a QR code. A unique feature of the system is its ability to predict the remaining shelf life of the product based on the dynamics of monitored parameters. The machine learning algorithms, trained on a large dataset of experimental results, can accurately (up to 92%-95%) forecast the point at which critical quality thresholds are reached. This enables optimised logistics and reduced product losses due to expired shelf life.

Experimental testing of the system at a dairy processing facility demonstrated that its implementation led to a 35%-40% reduction in product returns due to non-compliance with quality standards and improved supply chain efficiency through better inventory management. Additionally, the system provides full traceability from producer to consumer, enhancing brand trust and aligning with current trends in the food industry. The economic assessment of the proposed technological solutions demonstrated their competitiveness compared to traditional methods. Specifically, the implementation of a combined technology (high-pressure milk processing and antimicrobial packaging) enables a 20%-25% reduction in energy consumption relative to conventional thermal pasteurisation, and extends the product's shelf life by three to four times, significantly enhancing distribution opportunities. A detailed analysis of the energy efficiency of various milk processing technologies revealed that pulsed electric field treatment has the lowest energy consumption among the methods studied, at just 0.05 kWh/L. This is due to the process operating at room temperature, with energy expenditure limited to generating the electric pulses. Although high-pressure processing involves

substantial capital investment in equipment, it also shows strong energy efficiency (0.08 kWh/L) compared to traditional high-temperature pasteurisation (0.18 kWh/L). In the long term, these technologies offer the potential to substantially reduce operational costs and the environmental footprint of production.

The economic feasibility of implementing the developed technologies at a medium-capacity dairy facility (processing 50 tonnes of milk per day) showed that the capital investment in non-thermal processing equipment can be recouped within 2.5 to 3 years due to reduced operating costs, higher product yields, and expanded market reach. For enterprises producing premium segment products, the payback period may be reduced to 1.5 to 2 years, owing to the potential for premium pricing of products with enhanced sensory qualities and extended shelf life. The analysis of current trends in the food industry has identified several promising directions for the development of innovative technologies in the dairy sector. Among these, 3D printing of dairy products stands out as particularly noteworthy, enabling the creation of complex structures from dairy-based materials with customised properties. An experimental 3D-printing unit for dairy applications was tested using cheese mass enriched with probiotics. The results demonstrated that this technology allows for the formation of products with intricate internal structures and controlled release of active compounds (Dinkçi *et al.*, 2019; Alirezalu *et al.*, 2020). Testing of various formulations for 3D printing revealed that protein concentrate-based mixtures supplemented with hydrocolloids (such as pectin, gelatine and agar) serve best as structure-forming agents. These compositions ensure stable shape retention of printed structures during storage while maintaining acceptable sensory qualities. Enrichment with probiotic cultures enables the production of functional foods with targeted health-promoting properties.

Another promising direction is fermentation using immobilised cultures, which involves

fixing starter cultures onto specialised carriers to enhance their stability and productivity. Experimental research has shown that the use of immobilised cultures can reduce fermentation time by 35%-40% and increase the yield of bioactive compounds. Various materials were tested as carriers for immobilisation, including calcium alginate, carrageenan, chitosan, and synthetic polymers. The best results in terms of culture viability and technological feasibility were achieved using calcium alginate. Microscopic analysis showed that the starter culture cells were evenly distributed within the carrier matrix and maintained their metabolic activity over an extended period (up to 30 fermentation cycles with repeated use). Lyophilised methods for producing dry fermented products represent another promising area of research. This technology combines fermentation with subsequent freeze-drying, allowing the preservation of probiotic viability and the bioactive properties of fermented products. It was found that freeze-dried cultured dairy products retained up to 80%-85% of viable probiotic cultures after 12 months of storage at room temperature. Optimisation of the freeze-drying process revealed that pre-freezing the product at -40°C, followed by drying at a pressure of 0.1 mbar and plate temperature of 30°C, provided the best retention of probiotics and bioactive compounds. The addition of protective agents such as trehalose and inulin prior to drying further increased probiotic survival by 15%-20%. The resulting lyophilised products were characterised by high porosity, rapid rehydration when water was added, and the preservation of sensory properties comparable to those of fresh fermented products.

A comprehensive study of the rheological properties of reconstituted lyophilised fermented dairy products revealed that their consistency depends on the composition of the protective media used prior to drying. The addition of prebiotics, such as inulin and fructooligosaccharides, not only enhances the survival rate of probiotic cultures but also improves the texture of the reconstituted product, giving it a creamy consistency

similar to that of fresh yoghurt. Furthermore, these components increase the functional value of the final product by creating a synbiotic complex. Research into the microstructuring of dairy proteins using a combined approach – including controlled fermentation, high-pressure processing, and ultrasound treatment – has enabled the development of new types of protein ingredients with unique functional properties. It was found that such ingredients exhibit significantly higher water-holding capacity (by 30%-35% compared to traditional dairy protein concentrates), improved emulsifying properties, and the ability to form thermostable gels at low protein concentrations (3%-4%). The microstructured protein ingredients were successfully applied in the production of low-calorie dairy desserts, where they allowed for a 50%-60% reduction in fat content without compromising the sensory qualities of the product. Instrumental profilometry analysis of the texture of these desserts demonstrated that their rheological properties were comparable to traditional high-fat analogues, and in some instances, even surpassed them in terms of homogeneity and creaminess. Automated control systems incorporating artificial intelligence demonstrate considerable potential for optimising technological processes in the dairy industry. An experimental system for predicting the shelf life of dairy products, based on neural networks, achieved an accuracy rate of 92%-95%, enabling optimisation of logistics and a reduction in product waste.

To train the neural network, a large dataset was collected and analysed. This included changes in physicochemical, microbiological, and organoleptic parameters of various dairy products during storage under different conditions. A multilayer perceptron neural network with three hidden layers was trained on 80% of the available data, with validation carried out on the remaining 20%. The results showed that the system could accurately predict the residual shelf life of products based on an analysis of initial parameters and storage conditions (Fadiji *et al.*, 2023). In addition to shelf-life prediction, the developed

artificial intelligence system was adapted to optimise the processing conditions in dairy product manufacturing. Machine learning algorithms analysed correlations between raw material processing parameters (temperature, pressure, duration, etc.) and the quality characteristics of the final product. This allowed for the identification of optimal regimes to achieve the desired product properties with minimal energy and time expenditure. The practical implementation of an automated control system at a dairy facility significantly improved product quality consistency, reduced the proportion of defective batches by 40%-45%, and optimised the use of raw materials and energy resources. An additional advantage of the system lies in its capacity for continuous self-improvement through the accumulation of new data and refinement of predictive models.

An assessment of the energy efficiency of various technological combinations revealed that the most promising for industrial application is the integration of pulsed electric field treatment during the initial processing stage with high-pressure processing applied to the packaged end product. This combination enables a 30%-35% reduction in energy consumption compared to traditional technologies, while maintaining an equivalent or superior level of product safety. An evaluation of the environmental impact of innovative technologies, carried out using Life Cycle Assessment (LCA) methodology, indicated that non-thermal processing methods can reduce the carbon footprint of dairy production by 20%-25%, primarily by lowering energy consumption and decreasing food waste due to extended shelf life. Moreover, the use of biodegradable packaging materials modified with natural antimicrobial agents contributes to a further reduction in environmental burden (Morales-de la Peña *et al.*, 2019). A comprehensive analysis of the quality of dairy products produced using innovative technologies included not only standard physicochemical and microbiological parameters but also an assessment of the bioavailability of key nutrients. It was found that non-thermal

processing methods, such as high-pressure processing and pulsed electric fields, ensure greater bioavailability of calcium and essential amino acids compared to traditional thermal pasteurisation. This effect is attributed to a lower degree of protein denaturation and the preservation of the native structure of calcium-binding components in milk.

A study of the impact of innovative technologies on the allergenicity of milk proteins showed that high-pressure treatment (600 MPa, 15 minutes) can reduce the allergenic potential of β lactoglobulin – one of the main milk allergens – by 25%-30%. This is explained by pressure-induced conformational changes in the protein that result in the masking of certain epitopes responsible for allergic reactions. These findings open up opportunities for developing hypoallergenic dairy products using high-pressure processing instead of traditional thermal treatment. To evaluate the broader prospects for the implementation of innovative technologies in the dairy industry, a SWOT analysis was conducted. The key findings were as follows: strengths include improved product quality, extended shelf life, and increased energy efficiency; weaknesses involve high initial investment costs and the need for specialised personnel; opportunities relate to expanding the product range and entering new markets; threats stem from potential changes in regulatory requirements and consumer hesitancy towards new technologies. Marketing research conducted as part of this study showed that consumers are willing to pay 15%-20% more for dairy products produced using innovative “green” technologies that preserve the natural properties of milk. Willingness to pay a premium was particularly high among consumer segments focused on healthy lifestyles and environmental responsibility. Thus, the findings of this study demonstrate that innovative technologies for processing and manufacturing dairy products have considerable potential to improve production efficiency, enhance product quality, and extend shelf life. Combined approaches – integrating various methods of raw milk processing, product manufacturing, and

packaging, along with automated quality control systems – are especially promising.

Discussion

The study confirmed the high effectiveness of non-thermal milk processing methods and innovative packaging materials in extending the shelf life of dairy products. These findings should be viewed in the context of current scientific research in this field. The demonstrated high efficiency of high-pressure processing in microbial inactivation and minimal impact on organoleptic properties aligns with the results obtained by L. PicartPalmade *et al.* (2019). The authors noted that treatment at 500-600 MPa can achieve levels of microbial inactivation comparable to thermal pasteurisation, while ensuring significantly better preservation of thermolabile components in milk. They also conducted detailed studies on the impact of high pressure on specific microbial cultures and found that Gram-negative bacteria exhibit greater sensitivity to this method compared to Gram-positive strains. Studies have shown that high-pressure processing is particularly effective in accelerating cheese ripening. This aligns with the findings of A.Ch. Stratakos *et al.* (2019), who investigated the impact of high-pressure processing on the safety and quality of raw milk. Their research confirmed that the technology not only inactivates pathogenic microorganisms but also has a beneficial effect on enzymatic processes during cheese production, contributing to faster ripening and the development of a more intense flavour and aroma profile.

The results regarding the effectiveness of ultraviolet irradiation treatment in extending the shelf life of milk demonstrate significant microbial inactivation when applied in a thin layer. However, the issue of uneven exposure due to the shadowing effect in opaque liquids such as milk remains a limiting factor for large-scale applications. M.M. Delorme *et al.* (2020) proposed innovative technical solutions to address this challenge, including the use of turbulent flow and specially designed reactors with a high surface-to-volume

ratio, which enable more uniform irradiation. They also established that UV treatment has a selective effect on different groups of microorganisms in milk, showing the highest efficacy against coliform bacteria and psychrotrophic microorganisms – both of which are major contributors to the spoilage of dairy products during storage. The theoretical aspects of applying ultraviolet irradiation for milk treatment are comprehensively discussed in the research of T. Koutchma (2019), who proposed mathematical models for calculating the effective radiation dose based on the optical properties of the product, equipment geometry, and the kinetics of microbial inactivation. The author also systematised data on the impact of UV radiation on the nutrient composition of milk and established that, under optimised processing conditions, up to 90%-95% of thermolabile vitamins are preserved – findings that are consistent with those obtained in the present study. In this research, pulsed electric field technology demonstrated strong potential not only for microbial inactivation but also for improving the technological properties of milk. Of particular interest is the influence of this method on fermentation processes and texture formation in fermented dairy products. These results complement the study by M.M. Goodarzi *et al.* (2020), who found that pulsed electric fields can stimulate the activity of starter cultures and accelerate fermentation by 15%-20% due to increased permeability of microbial cell membranes.

The data obtained regarding the effectiveness of ultrasound treatment are supported by the findings of R. Mahendran *et al.* (2019), who investigated the use of pulsed light to extend product shelf life. Although the authors focused on a different technology, their conclusions on the mechanisms of microbial inactivation and the optimisation of processing parameters closely align with the results of the present study. In particular, they found that combining pulsed light with other non-thermal methods (including ultrasound) produces a synergistic effect, allowing for a higher degree of microbial

inactivation at less intensive processing levels, thus minimising the impact on the sensory and nutritional qualities of dairy products. The study of the effectiveness of automated quality control systems based on machine learning aligns with the findings of Z.H. Zhang *et al.* (2019), who conducted a comprehensive analysis of nonthermal technologies and their current and future applications in the food industry. The authors emphasised that the advancement of digital technologies and sensor systems is a key factor in the successful large-scale implementation of non-thermal processing methods. They proposed an integrated approach to process automation that includes continuous monitoring of critical processing parameters and product quality prediction using mathematical models – an approach closely aligned with the shelf-life prediction system for dairy products developed in the present study. The findings regarding the use of membrane technologies, particularly ultrafiltration, to increase protein concentration and improve the functional properties of dairy products complement the research by A. Soni *et al.* (2021). These authors analysed the application of emerging processing technologies aimed at enhancing the safety and bioactivity of milk. They demonstrated that membrane technologies not only enable the concentration of valuable milk components but also facilitate the removal of toxic substances and allergens, opening new opportunities for developing specialised products for specific consumer groups, including individuals with dairy protein allergies.

The study's findings on the impact of different processing methods on the allergenicity of milk proteins are supported by the research of H. Hernández *et al.* (2022), who explored the potential for developing innovative and healthier dairy products through the addition of microalgae. The authors found that certain components of microalgae, particularly polyphenols and peptides, are capable of binding to allergenic epitopes of milk proteins, thereby masking them and reducing the overall allergenicity

of the product. This insight opens up promising prospects for combining non-thermal processing methods with the addition of bioactive compounds to develop hypoallergenic dairy products. The effectiveness of combining various technologies, as demonstrated in this study, is supported by the research of N. Teixidó *et al.* (2022), who investigated the use of biological agents as alternatives to chemical preservatives. The authors conducted a comprehensive study of various bio-preservatives, including bacteriocins, the lactoperoxidase system, and natural extracts, and determined their effectiveness against the primary spoilage organisms in dairy products. The synergistic effect observed in this study when combining non-thermal processing methods with antimicrobial packaging materials complements the findings of M. Gogliettino *et al.* (2020). They established that the combination of high-pressure processing with active packaging materials containing antimicrobial peptides can extend the shelf life of meat and dairy products by two to three times compared with the use of each technology individually.

The findings on the development of intelligent packaging systems with freshness sensors are supported by the research of M.R. Yan *et al.* (2022), who analysed innovative packaging solutions in terms of quality, safety and consumer perception. The authors systematised various types of smart packaging, including temperature, time and freshness indicators, as well as QR codes and RFID tags for tracking product movement. They established that such systems not only provide improved quality control but also enhance consumer trust – an important factor in the adoption of new technologies within the food industry. The economic viability of introducing innovative technologies, as demonstrated in the present study, aligns with the conclusions of R. Vanaraj *et al.* (2024), who conducted a comprehensive assessment of the cost-effectiveness of different shelf-life extension technologies. The authors developed an integrated evaluation model that takes into account both

direct costs associated with equipment and its operation, and indirect benefits such as reduced product returns and the expansion of distribution networks.

Research into the development of functional dairy products using non-thermal processing methods complements the study of A. Sridhar *et al.* (2020), who examined the application of preservation technologies and nanotechnology for extending the shelf life of various food products. Particular attention was given to the relationship between processing methods and the bioavailability of functional ingredients, which is critical in the development of products with enhanced biological value. They found that non-thermal methods, such as high-pressure processing and pulsed electric fields, better preserve bioactive components and their functionality compared to conventional thermal technologies, which is fully consistent with the results obtained in this study. The environmental aspect of innovative packaging solutions explored in this study complements the findings of S. Pandey *et al.* (2022), who conducted a comprehensive analysis of current trends in active packaging. The authors assessed the life cycle of various packaging materials, including conventional polymers, biodegradable materials and nanocomposites, in terms of their environmental impact and potential for recycling or biodegradation.

Unlike previous studies, this research proposes a comprehensive approach to extending the shelf life of dairy products, encompassing the entire technological chain – from initial raw milk processing to packaging and storage of finished products. Such an approach maximises the efficiency of each technological solution through the synergistic interaction of different components within the system. The findings of the study lay the groundwork for the further development of innovative technologies in the dairy industry.

Conclusions

As a result of the study, a comparative analysis of modern innovative technologies for the

processing and treatment of dairy products was conducted. It was found that non-thermal methods – such as high-pressure processing, pulsed electric fields, ultrasound, and UV irradiation – ensure a higher retention of nutrients and superior organoleptic properties compared to conventional thermal processing. The most effective methods were high-pressure processing (600 MPa, 15 minutes) and pulsed electric fields (35 kV/cm, 1,000 Hz), which reduced the total microbial count by 4.2 and 3.8 log CFU/cm³, respectively, while preserving up to 91.8% of vitamin C and 96.5% of whey proteins. Combining these methods with antimicrobial packaging materials (silver nanoparticles, 1.5%) extended the shelf life of milk to 35 days. The study demonstrated the significant potential of non-thermal methods in dairy processing: ultrasonic treatment accelerated yoghurt fermentation by 28%-32%; high-pressure processing reduced cheese maturation time by 30%-35%; and ultrafiltration increased the yield of acid-set cheese by 15%-18%. Smart packaging systems with pH-sensitive indicators, combined with machine learning technologies, enabled shelf-life prediction with an accuracy of up to 92%-95%.

The energy efficiency of non-thermal technologies (0.04-0.08 kWh/L compared to 0.18 kWh/L for conventional pasteurisation)

contributes to a 20%-25% reduction in the carbon footprint of production. Economic analysis confirmed the commercial viability of implementing these technologies, with a payback period of 1.5 to 3 years, making them particularly attractive for producers of premium dairy products. Promising directions for future development include 3D printing of dairy products, fermentation using immobilised cultures, lyophilic technologies for the production of functional foods, and microstructuring of dairy proteins to create low-calorie products with enhanced sensory properties. An integrated approach that combines various innovative technologies for processing, treatment and packaging enables the production of safe, functional, and energy-efficient dairy products that meet the demands of the modern market, consumer preferences, and the principles of sustainable food industry development with minimal environmental impact.

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Conflict of Interest

None.

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Використання інноваційних технологій для збільшення терміну придатності молочних продуктів

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Анотація. Метою дослідження було надати комплексну оцінку впливу інноваційних технологій на процеси обробки та переробки молочних продуктів з метою подовження строку їх придатності. Порівняльний аналіз нетермічних методів показав, що найвищу ефективність інактивації мікроорганізмів забезпечують технологія високого тиску (600 МПа, 15 хв) та імпульсне електричне поле (35 кВ/см, 1000 Гц), які знижують загальну кількість мікроорганізмів на 4,2 та 3,8 \log КУО/см³ відповідно. Нетермічні методи демонстрували менший вплив на нутрієнтний склад молока порівняно з традиційною пастеризацією, забезпечуючи збереження до 91,8 % вітаміну С та до 97,2 % сироваткових білків. Найкращі органолептичні характеристики спостерігалися у зразках, оброблених технологією високого тиску та імпульсним електричним полем (4,9 бала за 5-бальною шкалою). Встановлено, що ультразвукова обробка прискорює ферментацію йогуртів на 28-32 %, високий тиск прискорює дозрівання сирів на 30-35 %, а ультрафільтрація підвищує вихід кисломолочного сиру на 15-18 %. Серед антимікробних пакувальних матеріалів найвищу активність продемонстрували плівки з наночастинками срібла (1,5 %). Виявлено синергетичний ефект при комбінованому застосуванні нетермічних методів обробки та інноваційних пакувальних матеріалів, що дозволяє збільшити термін придатності молока до 35 діб при температурі $4 \pm 1^\circ\text{C}$. Розроблено інтелектуальні пакувальні системи з рН-чутливими індикаторами для моніторингу свіжості продукту. Для дослідження синергетичного ефекту комбінованої обробки застосовувалося факторне планування експерименту з розрахунком коефіцієнтів синергії. Аналіз міграції наночастинок з пакувальних матеріалів показав, що їх концентрація не перевищувала допустимих рівнів при дотриманні рекомендованих умов зберігання. Розроблено математичні моделі для прогнозування

терміну придатності молока залежно від параметрів обробки та пакування. Проведено економічну оцінку запропонованих технологічних рішень, яка показала їх конкурентоспроможність порівняно з традиційними методами при виробництві продукції преміального сегменту

Ключові слова: нетермічна обробка; високий тиск; імпульсне електричне поле; антимікробне пакування; наночастинки; інтелектуальні пакувальні системи