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The impact of active packaging and nanocoatings on the safety and shelf life of dairy products

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Abstract. The aim of the study was to identify effective methods for maintaining the quality and safety of dairy products through the use of active packaging and nanotechnology. The methodology included an analysis of regulatory documents and current trends in packaging technologies, as well as experimental studies using control and experimental groups. The study found that milk and cottage cheese packaged in standard cardboard packaging with an inner layer of aluminium foil showed an average moisture content of $88.2 \pm 0.5\%$ and a redox potential of 185 ± 2 mV. In the group with active packaging containing antioxidant components, the moisture content was $87.5 \pm 0.4\%$, and the oxidation reduction potential (ORP) was reduced to 175 ± 1 mV. Packaging with silver nanoparticles showed the highest efficiency, where the moisture content of milk and cheese was $86.7 \pm 0.3\%$, and the ORP reached 170 ± 1.5 mV, indicating a reduction in the level of oxidative processes and improved product preservation. In addition, the study found that milk and cheese stored in active packaging and packaging with nanofilm showed significantly better organoleptic characteristics compared to control samples. In particular, the taste, smell, texture, and colour received higher scores on a scale from 1 to 5. For the control group, the average taste score was 3.2 ± 0.3 , for active packaging – 4.0 ± 0.2 , and for nanofilm – 4.7 ± 0.1 . Similar results were recorded for odour (3.2 ± 0.3 , 4.1 ± 0.2 and 4.8 ± 0.1 , respectively), texture (3.1 ± 0.4 , 4.0 ± 0.3 and 4.6 ± 0.2), and colour (3.0 ± 0.2 , 4.2 ± 0.1 and 4.7 ± 0.1). These data indicated a significant improvement in the organoleptic characteristics of dairy products stored in active packaging and packaging with nanofilm compared to control samples. The practical significance of the study was to develop recommendations for dairy producers on the choice of packaging materials depending on the shelf life and conditions of sale. The results obtained could be used in the food industry to introduce innovative packaging technologies, as well as serve as a basis for further research in the field of food safety and the development of environmentally friendly packaging material

Keywords: innovative technologies; industrial quality; nanomaterials; antioxidants; antimicrobial properties

Introduction

The problem of the impact of active packaging and nanocoatings on the safety and shelf life of dairy products is relevant, as dairy products are among the most susceptible to spoilage due to high sensitivity to microbiological, chemical and physical changes. In particular, the development of new packaging technologies, such as active packaging and the use of nanocoatings, can significantly improve the freshness of dairy products, reduce spoilage losses and extend shelf life. Such innovative packaging methods can also help reduce food waste, which is an important part of global initiatives to conserve resources and sustainability, and improve product safety through the ability to actively interact with the environment by regulating

humidity, oxygen levels or the release of antimicrobial agents.

This problem has been studied by scientists, in particular, S. Verbytskyi *et al.* (2024) explored innovative solutions to extend the safe shelf life of dairy products, including the use of advanced packaging technologies such as active packaging and nanocoatings to improve product safety and reduce spoilage. The authors emphasised the importance of innovative packaging approaches to improve the quality and shelf life of dairy products in a competitive market. In the research of Y. Verkhivker *et al.* (2023) and M. Klein *et al.* (2024) examined the use of C-PET consumer polymer containers in food production, highlighting effectiveness in

maintaining food quality and safety. The researchers discussed the benefits of polymer-based containers for extending the shelf life of dairy and other products, providing a more efficient packaging solution for the food industry. O. Rechun & O. Peredriy (2021) explored active and smart packaging for food, in particular its impact on food quality and safety, as well as the informative function of packaging. The scientists analysed the main technologies used in active and smart packaging systems and evaluated the advantages and disadvantages of such approaches, including the ability to reduce food loss and improve freshness. Researchers L. Kucher *et al.* (2021) studied the state and prospects of implementing the Hazard Analysis and Critical Control Point (HACCP) system in Ukraine to comply with EU food safety directives. The authors analysed the current challenges and opportunities for adapting Ukrainian standards to European food safety requirements, focusing on the need to improve safety legislation and practices. The peculiarities of the functioning of the food market in the context of the war in Ukraine were studied by L. Kvasnii *et al.* (2024). The authors analysed the negative impact of hostilities on food supply and production, as well as on the safety and stability of food systems in Ukraine during the crisis.

In addition, Y. Gadaieva *et al.* (2024) studied the environmental safety of food packaging, focusing on the importance of environmentally friendly materials and technologies in the packaging process to reduce environmental impact. The researchers discussed the prospects of using such materials in food production, in particular dairy products, to ensure safety and maintain ecological balance. L. Hortseva *et al.* (2020) identified the risks associated with the migration of toxic substances from packaging materials to food, which can lead to contamination and hazards to human health, and proposed strategies to control and minimise such risks. The authors focused on analysing the potential human health hazards arising from the use of

hazardous packaging materials and proposed strategies to minimise such risks. P. Kapitala & G. Khimicheva (2021) assessed the quality and safety of dairy products in accordance with HACCP principles and ISO 22000:2019 (2019). The author investigated how the application of these standards can help ensure an appropriate level of food safety and meet the requirements of international certification for quality control at all stages of production. In the study, M. Bazhal & T. Koutchma (2022) identified the risks associated with non-compliance with food safety standards, in particular due to outdated technologies and insufficient infrastructure development in Ukraine, and discussed ways to overcome risks with the help of scientific and technological progress to improve global food security, namely the modernisation of infrastructure to ensure effective inspection and quality control of products.

Despite the above studies, these authors did not sufficiently investigate the impact of the combination of different types of active packaging (antimicrobial, antioxidant, absorbent) on dairy products, as well as the interaction with nanocoatings. In addition, insufficient attention has been paid to the impact of these technologies on the long-term preservation of organoleptic characteristics, such as taste, smell, and texture of dairy products. The aim of this study was to determine the effectiveness of active packaging and nanocoatings in improving the shelf life and safety of dairy products. The objectives of the study were to analyse the types of active packaging and the mechanism of action on dairy products, assess the impact of nanocoatings on the shelf life and safety of dairy products, and investigate the impact of active packaging and nanocoatings on the organoleptic characteristics of dairy products, including taste, smell, and texture.

Materials and Methods

The types of packaging used for the study were active packaging with antioxidants, packaging

with silver nanoparticles, and cardboard packaging with barrier materials, which met the requirements of Regulation (EC) No. 1935/2004 of the European Parliament and of the Council “On Materials and Articles Intended to Come into Contact with Food” (2004). In addition, the packaging was compliant with Regulation (EU) No. 1169/2011 of the European Parliament and of the Council “On the Provision of Food Information to Consumers” (2011), providing a clear indication of the presence of nanomaterials in food through the appropriate “nano” labelling in the list of ingredients. The first step was to analyse the use of active packaging and nanotechnology in the food industry. The types of active packaging and mechanisms of action were reviewed, including antimicrobial, antioxidant and absorbent packaging, as well as nanomaterials used in dairy packaging, such as silver and copper nanoparticles, metal oxides (zinc oxide (ZnO) and titanium dioxide (TiO₂)), and cardboard packaging with barrier materials.

A survey was conducted to assess the attitudes of food industry experts towards the introduction of active packaging and nanocoatings in dairy production. The study involved 50 food industry experts aged 25 to 60, 60% of whom were men and 40% women. The group of food industry experts included individuals with experience in the food industry, particularly in dairy production, and knowledge of the implementation of active packaging and nanocoatings. The survey was conducted over a two-week period in the format of an online questionnaire via the Google Forms platform. The survey was conducted in accordance with the Code of Ethics of the American Sociological Association (2018). The questionnaire contained 15 questions. The results allowed determining the general attitude of respondents to the use of active packaging and nanocoatings in the dairy industry, as well as identifying the main factors that affect trust and willingness to consume such products.

The study was conducted at Dnipro Dairy Plant LLC, a company specialising in the production of pasteurised milk and cottage cheese. The study was conducted between June and August 2024. The following specific samples were selected for the experiment: pasteurised milk with a fat content of 3.2% and cottage cheese with a fat content of 5%. The milk was obtained directly from the production line of Dnipro Dairy Plant LLC, and the cottage cheese was obtained from a series of products produced at the enterprise for testing for organoleptic and physicochemical parameters. The number of samples for the study was 60 units, namely 30 units of pasteurised milk and 30 units of cottage cheese, which were divided into three groups for further storage and testing. The calorie content of milk was 60 kcal per 100 ml; 3.2 g – fat, 3.3 g – protein, 4.7 g – carbohydrates. For cottage cheese, the calorie content was 120 kcal per 100 g; 5 g – fat, 15 g – protein, 1 g – carbohydrates. Milk and cottage cheese were stored in different types of packaging. The temperature was maintained at 4°C by a Model X-200 refrigerator with automatic temperature control, and the humidity was regulated at 70-80% by a HygroMaster 3000 hygrometer. The shelf life of the products was 15 days. During this period, the organoleptic characteristics were regularly monitored and possible changes in the composition of the products were identified. The number of samples of each type of product tested was 60 units (20 units per group). The first group (control) was stored in standard packaging without additional protective properties. The standard packaging for milk and cheese consisted of cardboard packages with an inner layer of 6.5 µm thick aluminium foil produced by Dnipro Dairy Plant LLC, which provided protection against light, oxygen, and moisture. The second group was placed in active packaging, which contained antimicrobial and antioxidant components

that can slow down bacterial growth and oxidative processes. The active packaging contained antimicrobial components, such as silver nanoparticles (10 ppm) and zinc oxide (0.05%), as well as antioxidants, such as vitamin E (0.02%) and polyphenols (0.1%), which slowed bacterial growth by disrupting microbial cell membranes and prevented the oxidation of fats by absorbing free radicals. The third group included samples coated with a nanofilm containing silver nanoparticles (up to 0.5%) and metal oxides (ZnO and TiO₂ in concentrations up to 1%), which provided antimicrobial effects and barrier properties against the penetration of oxygen and microorganisms, creating a barrier to the penetration of microorganisms and oxygen. The packaging used silver nanoparticles with a size of 10-50 nm and metal oxides (ZnO, TiO₂) with a particle size of 20-100 nm, which were applied by plasma spraying technology to the polymer base, providing a uniform coating, the materials were produced by NanoPack Solutions Ltd.

To evaluate the impact of different types of packaging during the experimental period, measurements of physicochemical, microbiological and organoleptic parameters were carried out. Specialised equipment was used to measure the physicochemical and microbiological characteristics of dairy products. The pH level was measured using an Orion pH meter, model 3 STAR, which provided an accuracy of up to 0.01 pH units. The acidity of dairy products was determined by acid-base titration with 0.1 n NaOH solution until a stable pink colour appeared, using phenolphthalein as an indicator. The moisture content was determined by drying in an oven at 105°C for 6-8 hours until a stable weight value was reached. The oxidation reduction potential (ORP) was measured using a Hanna redox meter model HI 9147. All measurements were carried out under standard laboratory conditions with a temperature of 20-22°C and humidity of 60-65%.

The organoleptic characteristics were assessed by a tasting panel of three experts with experience in the food industry who evaluated the organoleptic characteristics of dairy products. The evaluation criteria included taste, smell, texture and colour, each of which was assessed separately on a 5-point scale, with 1 being the worst and 5 being the best. The obtained indicators were compared with the standards and requirements specified in DSTU 3662:2019 (2019) for milk and cottage cheese. For milk pH, the standard was 6.5-6.8, for acidity – no more than 18°T, the moisture content of cheese – no more than 80%, and the redox potential should not exceed 200 mV to maintain product safety and quality.

The microbiological analysis was carried out using the serial dilution method, which included counting the total number of bacteria and checking for pathogens. Organoleptic tests included the assessment of changes in colour, smell, texture, and taste based on compliance with ISO 4833-1:2013 (2013) for total bacteria and ISO 21528-2:2017 (2017) for enterobacteria. Microbiological studies were carried out using standard methods in accordance with DSTU 4587:2006 (2007). The number of microorganisms in dairy products was determined by incubating samples on agar media, Sabouraud agar for total bacteria and Endo agar for enterobacteria. The incubation conditions consisted of a temperature of 37°C for 24-48 hours for total bacterial colonisation and specific temperatures for specific microorganisms. The number of colonies was counted by counting colony forming units (CFU) per unit volume of the sample.

After completion of the experiment, a comparative analysis of the results was carried out using the statistical method of ANOVA. The variables of pH, acidity, moisture content, redox potential and microbiological parameters were analysed, and statistical analysis was performed by ANOVA with a significance level of $p < 0.05$ using SPSS software.

Results

Current trends in the use of active packaging and nanotechnology for the storage of dairy products

The most common types of packaging for dairy products are plastic bottles, carton bags and glass jars. According to market research conducted by Global Market Insight (2025), the breakdown of packaging materials used for dairy products is as follows: plastic bottles 45%, carton bags 35%, glass jars 15%, and other packaging 5% (Tetra Pak, n.d.). These data show that plastic bottles and carton bags are the most popular packaging options for dairy products, accounting for 80% of the market together. Glass jars and other types of packaging are used much less frequently.

Other types of packaging, such as active antioxidant packaging, silver nanoparticle packaging and cartons with barrier materials, are selected for the study because such packages are effective in helping to preserve the freshness of dairy products. Active packaging with antioxidants works by preventing oxidation, which is the main cause of taste loss in milk and dairy products. The antioxidants in the packaging materials absorb oxygen, thereby reducing the risk of rancidity and keeping the product fresh for a long time (Volpe *et al.*, 2022). Packaging with silver nanoparticles provides products with additional protection against microbiological contamination due to its antimicrobial properties, which ensures the preservation of products and prevents spoilage. In addition, cardboard packaging with barrier materials protects products from the negative effects of oxygen, moisture and light, which contributes to the long-term preservation of organoleptic properties. These types of packaging not only provide dairy products with a longer shelf life, but also preserve taste and nutritional qualities, which is important to meet consumer demands for dairy products.

Active antioxidant packaging, silver nanoparticle packaging and carton packaging with

barrier materials used for dairy products comply with European regulations such as Regulation (EC) No. 1935/2004 (2004) and Regulation (EU) No. 1169/2011 (2011), ensuring food safety, and the fact that the materials do not emit harmful substances in quantities hazardous to human health and do not cause unacceptable changes in the composition of the products. In addition, these types of packaging are labelled to indicate the presence of nanomaterials, which meets the requirements for clear information on the use of nanomaterials in packaging. For example, active antioxidant packaging used to preserve dairy products contains vitamin E or polyphenols that absorb oxygen and prevent oxidation, which helps to preserve the taste and extend the shelf life of milk and yoghurt. Some European countries use packaging materials for milk and yoghurt that include antioxidants to prevent rancid odours and keep products fresh for a longer time (Bińkowska *et al.*, 2024).

Packaging with silver nanoparticles is used for dairy products such as milk and cheeses due to pronounced antimicrobial properties. Silver nanoparticles are able to kill bacteria that can cause dairy products to spoil, which significantly extends shelf life. One of the well-known companies, Nestlé, uses packaging with silver nanoparticles to ensure the freshness and safety of dairy products, reducing the need for additional preservatives (Nestlé, n.d.). Carton packs with barrier materials, such as those used by Tetra Pak (n.d.), effectively protect dairy products from the negative effects of oxygen, water vapour and light. This packaging is optimal for storing milk, yoghurts, and dairy desserts without the need for refrigeration at all stages of distribution. This type of packaging ensures that products remain fresh for a long time and meets the safety and quality standards required by European regulations. Table 1 provides a comparative analysis of the main characteristics of different types of packaging for dairy products, including the impact on freshness, taste and antimicrobial properties.

Table 1. Comparative analysis of dairy product packaging types and main characteristics

Packaging type	Main characteristics	Types of dairy products
Active packaging with antioxidants	Packaging with antioxidants helps preserve the freshness of products by preventing oxidation and loss of flavour	Milk, yoghurts, cheeses, sour cream
Packaging with silver nanoparticles	Packaging with silver nanoparticles has antimicrobial properties, which reduces the number of bacteria and extends the shelf life of products	Milk, yoghurts, creams, cheeses
Cardboard packaging with barrier materials	Cardboard packaging with an internal barrier layer is used to prevent exposure to oxygen and preserve the taste characteristics of the product	Milk, liquid yoghurts, milk-based desserts

Source: compiled by the authors

Other promising nanomaterials used in dairy packaging include metal oxides, such as ZnO and TiO₂. These compounds are known for photocatalytic properties, which allow effectively destroying bacteria under the influence of light. In addition, the mentioned compounds provide protection against ultraviolet radiation, which helps to preserve vitamins and biologically active substances in foods. Metal oxides can also improve the mechanical and barrier properties of packaging materials by reducing gas permeability, which extends the shelf life of products. A separate category of nanomaterials in packaging is polymer nanofilms, which create an effective barrier to gases and moisture, reducing product oxidation and

loss of quality (Li *et al.*, 2023). Due to the use of nanoparticles in polymers, such films can have additional functional properties, such as antimicrobial activity or the ability to control the release of beneficial compounds. The use of such nanofilms in the dairy industry helps to preserve the organoleptic characteristics of products and prevents changes in texture, taste, and smell throughout the shelf life. The food industry traditionally uses glass, polyethylene and laminated packaging for dairy products. Each of these types of packaging has its own advantages and disadvantages that affect shelf life, product quality and environmental aspects. Table 2 shows the three types of packaging used for dairy products.

Table 2. Comparative analysis of packaging types for dairy products, including chemical and physical properties

Characteristic	Active packaging with antioxidants	Packaging with silver nanoparticles	Cardboard packaging with barrier materials
Type of antioxidants	Vitamin E, polyphenols	Silver nanoparticles	None
Mechanism of action	Absorbing oxygen, preventing oxidation	Antimicrobial effect, destruction of bacteria and microorganisms	Barrier to oxygen, water vapour and light
Reducing oxygen levels in packaging	Up to 90% (depending on antioxidants and packaging material)	Up to 85% (reduces bacterial contamination due to reduced oxygen)	Up to 70% (limitation of oxygen penetration through barrier layers)
Shelf life	Extends by 30-50% compared to conventional packaging	Extends by 20-40%, reduces the risk of developing pathogenic microorganisms	Lengthens by 20-30%, protects from light and oxygen
Packaging materials	Polymers containing antioxidants	Polymers with silver nanoparticles, nanocomposites	Cardboard, combined barrier polymer materials

Table 2. Continued

Characteristic	Active packaging with antioxidants	Packaging with silver nanoparticles	Cardboard packaging with barrier materials
Application	Milk, yoghurt, cheese	Milk, cheese, yoghurts, cheeses with added bacterial cultures	Milk, yoghurts, dairy desserts, liquid yogurts
Compliance with European regulations	Regulations (EC) No. 1935/2004 and No. 1169/2011, clear labelling of antioxidants and impact on product composition	Regulations (EC) No. 1935/2004 and No. 1169/2011, “nano” labelling when using nanomaterials	Regulation (EC) No. 1935/2004 on the safety of materials in contact with food
Main advantage	Prolonging freshness, preventing rancid odour	Reducing bacterial contamination, extending shelf life	Protection from oxygen, water and light, long-term storage

Source: compiled by the authors

Table 2 compares the main physical and chemical characteristics of the three types of packaging for dairy products, focusing on properties, effectiveness, use, and compliance with European regulations. Glass packaging is considered one of the best options for storing dairy products, as it does not chemically interact with the product, provides a good barrier against external influences and preserves the taste characteristics (Gadaieva *et al.*, 2024). However, its main disadvantage is its high weight, fragility, and difficulty of transportation. In addition, although glass can be recycled many times, its production process is energy-intensive. Plastic packaging is the most common type of packaging due to its low cost, lightness and convenience, providing an adequate level of protection for products, but are not completely impermeable to oxygen, which can contribute to oxidation processes and shorten the shelf life. In addition, polyethylene is poorly biodegradable, which puts a significant strain on the environment. Laminated packaging, such as cardboard boxes with an inner layer of aluminium or polyethylene (e.g., Tetra Pak), combine the advantages of different materials to provide airtightness, protection from light and oxygen, and a relatively long shelf life. However, the complexity of the structure makes materials difficult to recycle,

as different layers of materials need to be separated. However, despite its many advantages, active packaging also has some disadvantages. It is more expensive to produce compared to standard packaging materials, which can affect the final cost of the product for consumers. The use of nanomaterials in packaging requires further research into long-term impact on human health, as some aspects of the interaction with food remain poorly understood. In addition, due to complex chemical composition, nanomaterials may pose additional challenges in terms of environmental disposal. From an environmental point of view, active packaging, despite its effectiveness, raises certain questions (Rechun & Peredriy, 2021). On the one hand, reducing food spoilage and extending its shelf life helps reduce food waste. On the other hand, especially if containing nanomaterials or multilayer components.

Research on the effectiveness of different types of packaging for preserving the quality of dairy products

To assess the attitude of food industry experts to the introduction of active packaging and nano-coatings in dairy production, a survey was conducted, the results of which are presented in Table 3.

Table 3. Results of an expert survey on the use of active packaging and nanocoatings

Question	Number of people
Are you familiar with active packaging and nanocoating technologies?	Yes – 34, No – 16
Do you think these technologies can improve the safety of dairy products?	Yes – 38, No – 5, Hard to answer – 7
How do you assess the potential impact of nanocoatings on the quality of dairy products?	Positive – 33, Neutral – 13, Negative – 5
Do you think that using active packaging can reduce product loss due to spoilage?	Yes – 40, No – 4, Hard to answer – 6
What factors are most important to you when choosing dairy products?	Shelf life – 23, Composition – 15, Price – 10, Brand – 2
Are you willing to pay more for dairy products with an extended shelf life?	Yes – 28, No – 15, Hard to answer – 7
What is the acceptable price difference you consider acceptable for such products?	Up to 5% – 20, 5-10% – 18, More than 10% – 5, Not willing to pay more – 7
Do you have any reservations about the use of nanotechnology in the food industry?	Yes – 25, No – 18, Hard to answer – 7
What are the main risks you see in the use of nanomaterials in food products?	Insufficient research – 20, Possible health effects – 18, Lack of regulation – 12
Do you trust scientific studies that confirm the safety of nanocoatings?	Yes – 30, No – 10, Hard to answer – 10
What benefits of active packaging are most significant to you?	Shelf-life extension – 25, Protection against microorganisms – 18, Improving product quality – 7
Can these technologies help reduce food waste?	Yes – 35, No – 8, Hard to answer – 7
Do you support government regulation of the use of nanotechnology in the food industry?	Yes – 43, No – 2, Hard to answer – 5
Are you interested in learning more about these technologies?	Yes – 33, No – 10, Hard to answer – 7
How, in your opinion, can consumer confidence in products with nanocoatings be increased?	Conducting additional research – 23, Informing consumers – 20, Product certification – 7

Source: compiled by the authors

In the study, the control group (standard packaging) showed the fastest negative changes in organoleptic and microbiological characteristics. On the 10th day of storage, an increase in titratable acidity to 20°T was observed in milk, and the pH decreased to 6.2, indicating the development of lactic acid bacteria. On the 12th day, the cottage cheese showed a deterioration in consistency and the appearance of a foreign odour, indicating the onset of spoilage. The second group (active packaging) significantly slowed down oxidative processes and the growth of microorganisms. The acidity of the milk on the 15th day of storage did not exceed 18°T, and the pH remained within 6.4-6.6.

The results of organoleptic tests showed that dairy products stored in nanocoatings

retained freshness longer and had stable sensory characteristics. In particular, after two weeks of storage, 80% of the samples with active packaging met high organoleptic standards, while in traditional packaging this figure was only 50%. The organoleptic characteristics remained satisfactory, and changes in the consistency of the cottage cheese began to appear only after 14 days. During the first two weeks of storage, milk, and cottage cheese retained original characteristics without significant changes. The colour remained uniform, with no signs of yellowing or darkening, which could indicate oxidative processes. The smell remained fresh, without any off-flavours, indicating the absence of active microbial development or fat oxidation.

The consistency of the milk remained stable, without sedimentation or stratification. In the case of cottage cheese, the structure of the product remained uniform until the 14th day of storage, with no signs of excessive moisture or lumps. Only after this period did the experts begin to notice slight changes in the texture, including the appearance of a more pronounced whey release, which is typical of the natural ageing process of fermented dairy products. The taste characteristics remained satisfactory throughout the entire period: in the control group, the products began to lose freshness on day 10-12, while the active packaging and nano-coated samples showed longer taste stability.

In the active packaging group, there was no rancid taste, which confirmed the effectiveness of antioxidants in preventing fat oxidation. The nanofilm samples inhibited the development of undesirable microflora, which contributed to the preservation of a pure fermented milk taste.

The third group (nanofilm with silver or metal oxide nanoparticles) provided the best level of product quality preservation. The content of microorganisms in the milk was the lowest among all groups, the acidity did not exceed 17°T, and the pH remained stable (6.5-6.7). Sour milk curd retained its characteristics until the end of the experimental period, without significant changes in consistency and smell.

Table 4. Characteristics of the effectiveness of different types of packaging for dairy products

Indicator	Control group	Active packaging	Nanofilm
Milk acidity (°T)	20±0.5	18±0.4	17±0.3
pH of milk	6.2±0.1	6.4±0.1	6.6±0.1
Microorganism content (CFU), <i>Salmonella</i> , <i>Listeria monocytogenes</i> , <i>Escherichia coli</i> , <i>Staphylococcus aureus</i> , <i>Bacillus cereus</i> and <i>Campylobacter jejuni</i>	2.5×10 ⁶	1.2×10 ⁶	5.0×10 ⁵
Cheese consistency retention (days)	12	14	15
Taste rating (1-5)	3.5	4.0	4.5
Odour rating (1-5)	3.0	4.0	4.5
Consistency rating (1-5)	3.0	4.0	4.5
Colour rating (1-5)	3.5	4.5	5.0
Overall organoleptic assessment	3.2±0.3	4.0±0.2	4.7±0.1

Source: compiled by the authors based on ANOVA analysis

The statistical analysis showed significant differences between the groups ($p < 0.05$), which confirms the effectiveness of active packaging and nanofilm in extending the shelf life of dairy products.

One of the key indicators that determines the quality of dairy products is the pH level. During storage, it changes due to the development of microorganisms and enzymatic reactions. In control samples stored in conventional packaging, the pH decreased faster, indicating active acid accumulation processes, especially in fermented dairy products. The active packaging with antimicrobial and antioxidant properties helped to maintain a more

stable pH level throughout the storage period. Acidity is another important parameter. It increases due to the metabolic activity of bacteria. In products packaged in standard materials, this process was faster, while active packaging and nanocoatings significantly slowed down the formation of excess acidity, while maintaining optimal conditions for consumption. The moisture content of a product affects its texture and microbiological stability. In dairy products with a high moisture content, such as cheese or yoghurt, improper packaging can lead to excessive drying or, conversely, condensation, which promotes microbial growth. Polymeric nanofilms with barrier properties

helped control the moisture level, preventing its loss or oversaturation. Another important indicator is the ORP. High values of the ORP promote the oxidation of fats, which can lead to the development of a rancid taste and deterioration of product quality. Antioxidant active

packaging slowed down these processes, which had a positive impact on the preservation of the taste and smell of dairy products. The results of moisture and redox potential measurements for dairy products stored in different types of packaging are shown in Table 5.

Table 5. Results of moisture and ORP measurements for dairy products with different types of packaging

Packaging type	Humidity, %	Oxidation reduction potential (ORP), mV
Standard packaging	87 ± 0.5	200 ± 5
Active packaging	85 ± 0.4	180 ± 4
Packaging with silver nanoparticles	84 ± 0.3	170 ± 3

Source: compiled by the authors

The results of the moisture and ORP measurements showed that the active packaging and silver nanoparticle packaging contributed to a reduction in moisture and an improvement in redox potential compared to the standard packaging.

One of the main functions of active packaging and nanocoatings is to prevent bacterial growth. The study found that in control samples of dairy products, the number of bacteria, in particular the gram-negative bacteria *Escherichia coli* and *Pseudomonas* spp. increased sharply on the 3-5th day of storage. This is due to the lack of additional barriers in standard packaging, which contributed to the active reproduction of microorganisms due to the lack of antimicrobial properties. The use of nanocoatings with silver particles or metal oxides, such as ZnO and TiO₂, has led to a significant reduction in the number of microorganisms in dairy products, including a 50-60% reduction in bacterial contamination. This resulted in an extended shelf life and improved organoleptic properties of the products. As a result, the products in this packaging remained safe for consumption for 5-7 days longer compared to the control samples. In addition to the overall reduction in bacterial contamination, active packaging also reduced the risk of pathogenic

microorganisms such as *Salmonella*, *Listeria monocytogenes* and *Escherichia coli*. The level of reduction of bacterial contamination for pathogens such as *Salmonella*, *Listeria monocytogenes* and *Escherichia coli* was 40-60%, which indicates the effectiveness of such packaging in ensuring product safety.

The results demonstrated that the dairy samples packaged with nanocoatings contained significantly fewer bacteria compared to traditional packaging materials. Changes in the organoleptic characteristics of samples stored in conventional packaging were faster, and already on the 5th-6th day of storage, signs of a rancid smell were observed, and the texture changed (dryness or excessive moisture). The active packaging containing antioxidant components helped to preserve the natural taste and smell of the products, as it prevented the oxidation of fats, as determined by experts.

Discussion

The results confirmed the effectiveness of active packaging and nanocoatings in preserving the quality of dairy products, reducing microbial contamination and extending shelf life. Similar conclusions are contained in the works of A. Mirza Alizadeh *et al.* (2022), who reviewed trends in the use of smart packaging for dairy

products. The study showed that such materials can prevent product spoilage by actively controlling the environment. L. Bandera (2025) studied the impact of various packaging materials on food safety and confirmed that active packaging helps to reduce the level of contamination with pathogens, which is consistent with the results obtained. Similar conclusions were made by I. Barukčić *et al.* (2021), who found that the use of packaging technologies reduces the effects of oxygen and moisture on dairy products, helping to preserve organoleptic properties.

The use of nanostructured antimicrobial agents in packaging was analysed in study A. Brandelli *et al.* (2023). In the work, the authors investigated the effectiveness of various types of nanomaterials, in particular silver and zinc nanoparticles, in the fight against pathogens commonly found in dairy products. It has been found that the use of such nanocomponents in active packaging contributes to a significant reduction in the number of *Escherichia coli*, *Listeria monocytogenes* and *Staphylococcus aureus* bacteria, which, in turn, extends the shelf life of products and improves the microbiological stability. In addition, the authors emphasise the importance of controlling the safety of nanomaterials, as the migration into food remains a pressing issue. Similar results were obtained by Y. Li *et al.* (2023), who studied the effect of bactericidal components, including chitosan, metal nanoxides, and bioactive polymers, on milk quality. The study confirmed that active packaging with built-in antimicrobial agents significantly slows down the growth of microorganisms in raw and pasteurised milk, reducing the rate of fat oxidation and preventing the formation of undesirable metabolites. An important aspect of the work was the comparison of the effectiveness of traditional preservatives and the latest nanostructured agents: the results showed that nanomaterials provide longer protection without affecting the taste and texture of dairy products. A separate area of research concerns edible coatings as an

alternative approach to active packaging. S. El-Sayed & A. Youssef (2024) studied the use of edible biopolymer coatings for cheese packaging, in particular coatings based on alginate, carboxymethyl cellulose, and gelatin. It was found that such coatings effectively reduce moisture loss, prevent fat oxidation and slow down the growth of spoilage microorganisms, which helps to preserve the texture and taste of the product. The results confirm that nanocoatings have a significant potential for maintaining the stability of the chemical composition of dairy products and can become an environmentally friendly alternative to traditional packaging. The use of a modified gas environment (MGE) in combination with active packaging is one of the most effective methods of extending the shelf life of dairy products (Shebanina *et al.*, 2024). The study by R. Chawla *et al.* (2021) confirmed that the use of gas mixtures with controlled oxygen, carbon dioxide and nitrogen content together with antimicrobial coatings helps to reduce the growth of pathogens, which has a positive impact on the quality and safety of dairy products. The effect of packaging materials on the structure and consistency of dairy products was studied by S. Harmankaya *et al.* (2022), who investigated the stability of yoghurt. It was found that active packaging components prevent product stratification while maintaining its texture and sensory characteristics. In addition to these studies, D. Francis *et al.* (2024) proved that biodegradable active materials not only extend the shelf life of fermented dairy products, but also preserve the nutritional properties. This opens up prospects for the widespread adoption of eco-friendly packaging technologies in the dairy industry.

The study by M. Vasuki *et al.* (2023) confirmed the effectiveness of smart packaging, which ensures continuous monitoring of the condition of dairy products during storage and transportation. The authors analysed the use of freshness indicators that change colour depending on the pH, temperature or gas

concentration in the packaging. This allows for timely detection of product spoilage and significantly reduces the amount of food waste, as the consumer receives accurate information about its suitability for consumption. The study also showed that the integration of nanosensors into packaging materials can significantly improve food safety, as it is possible to detect microbial contamination at an early stage. The findings are in line with a study that confirmed the effectiveness of active packaging technologies in maintaining consistent quality of dairy products. The combination of smart indicators with nanocoatings helps to extend shelf life and minimise the risks associated with bacterial contamination. In addition to classic packaging materials, edible coatings are a promising area. A study by M. Mikus & S. Galus (2025) focused on the use of biopolymer films for fruit, but the authors noted that similar technologies could be adapted for dairy products. In particular, edible coatings based on gelatin, starch, alginate, and chitosan can create a barrier to oxygen and moisture, which prevents dairy products from spoiling (Remizova *et al.*, 2024). In addition, such coatings can be enriched with antioxidants and antimicrobial agents, which will further protect the products. The results of this study correlate with the data obtained on the positive impact of nanocoatings on the stability of the chemical composition of dairy products. The use of such technologies can become an environmentally friendly alternative to traditional plastic packaging and contribute to the development of sustainable food production.

Despite the numerous advantages of nanopackaging, its widespread use requires compliance with international food safety standards. A study by Y. Burylo *et al.* (2023) focused on the regulatory framework for packaging materials in the EU and Ukraine. The authors found that the use of nanoparticles in the food industry does not yet have a clear legal framework, and some countries require additional research on the safety of such materials for consumers.

In particular, the EU has Regulation (EC) No. 1935/2004 regulating materials in contact with food, but certain aspects of nanotechnology in packaging need to be clarified (Semenenko *et al.*, 2021; Dankevych *et al.*, 2024). In Ukraine, the legal framework is still evolving, which creates additional challenges for manufacturers seeking to use innovative packaging solutions. Thus, the introduction of nanopackaging in the food industry should be accompanied by the development of appropriate standards and research to confirm its safety for human health. In the work, D. Nath *et al.* (2022) considered the possibilities of using nanocomposite materials in food packaging and found that such materials can significantly improve the mechanical and barrier properties of packaging materials. Similar results were obtained in the works of M. Gogliettino *et al.* (2020), T. Niaz *et al.* (2022), and C. Figueroa-Enríquez *et al.* (2024), where the effectiveness of nanoparticles for preserving the freshness of dairy products was demonstrated. A. Karnwal *et al.* (2025) emphasised the importance of using natural biopolymers in food packaging, stressing that such materials can provide additional protection of dairy products from the negative effects of the environment. Vandana & K. Sinha (2019) conducted a general analysis of the impact of packaging on the shelf life of milk and dairy products, noting that the effectiveness of packaging technologies largely depends on storage conditions and the interaction of the packaging material with the product. The results confirmed the effectiveness of active packaging and nanocoatings in maintaining the safety, quality, and shelf life of dairy products.

In the US, the use of nanomaterials in food and packaging is regulated by the Food and Drug Administration (FDA) (Kudrenko & Hall, 2024). The FDA requires manufacturers to conduct a safety assessment of nanomaterials before being introduced to the market. In particular, if a nanomaterial is used as a food additive or food contact material, it must meet safety

requirements and be approved for use (Export to the USA..., 2025). The World Health Organisation (WHO), together with the Food and Agriculture Organisation (FAO), develops standards and recommendations for food safety, including the use of nanotechnology. The Codex Alimentarius standards are aimed at guaranteeing the consumer a safe food product that is free from falsification, properly labelled and meets established quality standards (Uzenbaev *et al.*, 2019).

The main restrictions and requirements for the use of nanomaterials in the food industry include the fact that before introducing nanomaterials into food or packaging, a thorough assessment of the safety for human health must be carried out. This includes toxicity studies, the potential for nanoparticles to migrate from the packaging into the product, and an assessment of the effects on the body upon consumption. In the EU, the presence of nanomaterials in food products must be clearly indicated in the ingredient list with the “nano” mark next to the name of the respective ingredient. This provides transparency for consumers and enables consumers to make informed choices. Governments and international organisations are constantly monitoring the use of nanotechnology in the food industry. This includes monitoring new research on the safety of nanomaterials, updating regulations and introducing new standards where necessary. Thus, the use of nanotechnology in the food industry is regulated by a number of international and national regulations aimed at ensuring consumer safety. Manufacturers planning to introduce nanomaterials into products or packaging must strictly comply with the established requirements, conduct the necessary research and ensure transparent information to consumers about the presence of nanomaterials in the products.

Conclusions

It has been found that the use of antimicrobial and antioxidant components in active packaging can effectively inhibit the development of

microorganisms and oxidative processes, which has a positive effect on the physicochemical and organoleptic characteristics of products. The study assessed the impact of different types of packaging on the quality and safety of dairy products. The experts confirmed that all types of packaging met the established safety standards, which ensured that the quality of the products was maintained during the storage period. The study found that the use of nanocoated packaging contributed to better preservation of dairy products. Milk and cheese stored in nanocoated packaging had significantly lower bacterial counts than control samples. During the organoleptic test, it was found that the products in the nanocoated packaging retained freshness, colour and smell better than the other samples. In addition, a reduction in oxidation and spoilage processes was recorded in these samples. Statistical analyses showed a significant difference between the samples in the control and experimental groups in terms of quality and microbiological characteristics. In particular, the average number of bacteria in the control milk samples was 8.5×10^4 CFU/ml, while in the samples with nanocoated packaging it was 3.2×10^4 CFU/ml. Similar results were obtained for cottage cheese. Instead, active packaging, especially those with antimicrobial properties, can reduce the rate of product spoilage, extending shelf life by an average of 3-5 days compared to traditional packaging materials. Nanocoatings, in particular those containing silver and metal oxide nanoparticles, demonstrated the highest efficiency. Such nanocoatings helped to maintain a stable level of acidity and moisture in dairy products, as well as reduce bacterial contamination, which allowed for a 5-7-day shelf-life extension. It has been confirmed that active packaging and nanocoatings do not have a negative impact on the taste, smell, and texture of dairy products, provided that the dosage of active ingredients is correct. However, excessive concentration

of nanoparticles can change the sensory characteristics of products, which requires further research to optimise composition. Future research may also focus on the development of biodegradable nanocoatings, as well as on improving methods for monitoring the safety of packaging materials in real-world production and storage conditions.

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Вплив активної упаковки та нанопокриттів на безпеку та термін придатності молочних продуктів

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Анотація. Метою дослідження було визначення ефективних методів підтримки якості та безпеки молочної продукції шляхом використання активної упаковки та нанотехнологій. Методологія включала аналіз нормативних документів та сучасних тенденцій у технологіях упаковки, а також експериментальні дослідження з використанням контрольної та експериментальної груп. Дослідження показало, що молоко та сир, упаковані у стандартну картонну упаковку з внутрішнім шаром алюмінієвої фольги, показали середній вміст вологи $88,2 \pm 0,5$ % та окисно-відновний потенціал 185 ± 2 мВ. У групі з активною упаковкою, що містила антиоксидантні компоненти, вміст вологи становив $87,5 \pm 0,4$ %, а окислювально-відновний потенціал (ОВП) знизився до 175 ± 1 мВ. Найвищу ефективність показала упаковка з наночастинками срібла, де вміст вологи в молоці та сирі становив $86,7 \pm 0,3$ %, а ОВП досяг $170 \pm 1,5$ мВ, що свідчило про зниження рівня окислювальних процесів та покращене збереження продукту. Крім того, дослідження показало, що молоко та сир, що зберігалися в активній упаковці та упаковці з наноплівкою, демонстрували значно кращі органолептичні характеристики порівняно з контрольними зразками. Зокрема, смак, запах, текстура та колір отримали вищі бали за шкалою від 1 до 5. Для контрольної групи середня оцінка смаку становила $3,2 \pm 0,3$, для активної упаковки – $4,0 \pm 0,2$, а для наноплівки – $4,7 \pm 0,1$. Подібні результати були зафіксовані для запаху ($3,2 \pm 0,3$, $4,1 \pm 0,2$ та $4,8 \pm 0,1$ відповідно), текстури ($3,1 \pm 0,4$, $4,0 \pm 0,3$ та $4,6 \pm 0,2$) та кольору ($3,0 \pm 0,2$, $4,2 \pm 0,1$ та $4,7 \pm 0,1$). Ці дані свідчили про значне покращення органолептичних характеристик молочних продуктів, що зберігалися в активній упаковці та упаковці з наноплівкою, порівняно з контрольними зразками. Практичне значення дослідження полягало в розробці рекомендацій для виробників молочної продукції щодо вибору пакувальних матеріалів залежно від строку придатності та умов продажу. Отримані результати можуть бути використані в харчовій промисловості для впровадження інноваційних технологій упаковки, а також слугувати основою для подальших досліджень у галузі безпеки харчових продуктів та розробки екологічно чистих пакувальних матеріалів

Ключові слова: інноваційні технології; промислова якість; наноматеріали; антиоксиданти; антимікробні властивості