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THE EFFECT OF INNOVATIVE STORAGE METHODS ON THE MICROBIOLOGICAL SAFETY INDICATORS OF RAW MATERIALS OF ANIMAL ORIGIN

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Summary. This article summarizes current scientific data on the impact of innovative storage methods on the microbiological safety indicators of raw materials of animal origin. The relevance of this topic stems from the fact that raw meat materials and their primary-processing products are among the most microbiologically vulnerable objects in food production due to their high moisture and nutrient content, as well as conditions that favor the growth of spoilage microflora, sanitary indicators, and potentially pathogenic microorganisms. The study aims to determine the impact of innovative storage methods on the microbiological safety of raw animal products. The research materials consisted of domestic and foreign scientific publications examining the impact of temperature conditions, cold chain stability, modified gas atmospheres, vacuum and active packaging, food coatings, and combined barrier technologies on the microbiological condition of meat. The study employed bibliographic, analytical, comparative, and generalization methods. The analysis revealed that traditional cold storage only slows the growth of microorganisms. It does not eliminate the risk of hazardous microorganisms proliferating. The article shows that breaking the cold chain leads to a deterioration of the microbiological characteristics of raw materials and reduces their safe storage life. Conversely, the use of modified gas atmospheres, active packaging, and edible coatings provides more effective inhibition of microbial growth. These methods also reduce surface contamination of raw materials and extend their microbiological stability period. The most pronounced antimicrobial effect was observed with combined technologies integrating temperature control and antimicrobial packaging or preservation agents. The article presents a comparative analysis of the shelf life of raw meat across preservation and packaging methods, demonstrating the advantages of innovative combined methods over isolated refrigerated storage. Therefore, innovative storage methods should be viewed as an effective means of managing the microbiological safety of raw materials of animal origin. Their effectiveness is determined not only by the choice of technology but also by adapting the storage method to the type of raw material, the initial microbial load, and the storage conditions. The practical significance of this work lies in the synthesis of approaches to improve technologies for the safe storage of raw meat and to minimize microbiological risks in food production

Keywords: meat products, microorganisms, cutting-edge technologies, safe storage

Introduction. Raw materials of animal origin are highly valuable but also particularly vulnerable to microbiological contamination in food production. Their high nutritional value, significant moisture content, and rich presence of nitrogenous compounds, lipids, vitamins, and minerals create ideal conditions for the growth of various microorganisms, including spoilage organisms, indicator microorganisms, and certain pathogenic agents. Thus, ensuring the microbiological safety of these materials poses a considerable technological, sanitary, hygienic, and socioeconomic challenge that is directly linked to the quality, shelf life, and safety of food products for consumers.

Raw meat products occupy a special place among raw materials of animal origin because they are susceptible to microbiological changes early in the storage process. Several factors influence the microbiological condition of meat, as established by [Bhat et al. \(2024\)](#), [Kukhtin and Salata \(2023\)](#), and [Pelykh, Konoplianko and Vinnyk](#)

[\(2024\)](#). The most important factors are primary contamination, temperature, storage duration, gas composition of the environment, packaging condition, water activity, pH, and adherence to the cold chain. [Doulgeraki et al. \(2012\)](#), [Kukhtin and Salata \(2023\)](#) have demonstrated that active microbiological and biochemical processes continue in raw meat even under refrigeration conditions. These processes may be accompanied by changes to the structure of the dominant microbiota, the accumulation of microbial metabolites, and the gradual deterioration of safety and quality indicators. Therefore, managing the microbiological risks associated with storing raw materials of animal origin requires more than traditional refrigeration. [Necidová et al. \(2024\)](#) demonstrated that breaking the cold chain significantly alters the microbiological profile of chilled poultry meat and reduces the effectiveness of technologically sound packaging and storage methods.

Analysis of scholarly sources. Pivovarov, Kovalova and Koshulko (2025), Oliinychenko, Tiwari and Stratakos (2026), and Oyewole, Izuafa and Ayomide (2026) report that there has been a significant shift in recent years in the approach to storing animal-derived raw materials. Previously, priority was given primarily to low-temperature storage; however, scientific interest is now shifting toward innovative storage regimes that combine temperature control, optimization of the gas composition of the packaging atmosphere, and the use of active and edible packaging, antimicrobial films, natural preservatives, bioactive metabolites, and combined non-thermal technologies. An innovative storage regime can be viewed as a set of organizational and technological conditions that exert targeted influence on the growth, survival, and metabolic activity of microorganisms in animal raw materials.

Heir et al. (2022) and Liang et al. (2024) have demonstrated that a modified gas atmosphere is one of the most promising areas in this field. Mortazavi et al. (2024) and Sai-Ut et al. (2025) demonstrated that elevated CO₂ levels in packaging systems inhibit the growth of harmful microorganisms and extend the period during which raw materials maintain acceptable safety and quality parameters.

Another important area of research is active packaging and edible coatings. Recent studies by Bhat et al. (2024) and Her, Han and Ha (2024) have investigated modified packaging materials. Ranjbar et al. (2025), Rupérez, Nerin and Silva (2025), Her, Han and Ha (2024), and Abbasi et al. (2023) have demonstrated that polylactic acid antimicrobial films and edible coatings made from polysaccharides, essential oils, menthol, and postbiotics effectively maintain the microbiological stability of chicken and lamb during refrigerated storage. An increasing number of scientific studies are examining innovative storage conditions that incorporate additional barrier factors. Qiu et al. (2025), Oliinychenko, Tiwari and Stratakos (2026), Gómez et al. (2020), Khalid et al. (2023), and Novikova, Pelykh and Vohnivenko (2023) have researched this issue. At the same time, a review of the literature indicates that the microbiological safety indicators of raw materials of animal origin cannot be assessed in isolation from their thermal state, pretreatment method, and initial technological characteristics. Domestic studies by Pelykh, Konoplianko and Vinnyk (2024) have shown that the thermal state of meat raw materials significantly affects their microbiological indicators and the safety of final products. This underscores the importance of properly organizing storage at the raw material stage. This principle is fundamental because it enables storage to be viewed as part of a unified system for ensuring the safety of raw materials throughout the production chain rather than as an isolated process that occurs after they have been received.

The study **aims** to determine the effect of innovative storage methods on the microbiological safety indicators of raw materials of animal origin.

Materials and methods. This study drew on 21 scientific sources devoted to storing raw materials of animal origin and their microbiological safety indicators, as well as modern, innovative preservation technologies. The literature review examined the impact of temperature regimes, modified gas atmospheres, active packaging, edible coatings, and combined antimicrobial approaches on the microbiological condition of meat raw materials, drawing on domestic and foreign publications. The study employed bibliographic, analytical, and comparative research methods. The impact of innovative storage conditions on the microbiological safety indicators of raw materials of animal origin was determined through a systematization of the literature, along with its critical analysis and synthesis.

Results. A review of the current scientific literature shows that innovative storage methods significantly impact the microbiological safety of raw materials of animal origin. According to Pivovarov, Kovalova and Koshulko (2025), Kukhtin and Salata (2023), and Pelykh, Konoplianko and Vinnyk (2024), the microbiological stability of these materials depends on the combined effects of temperature, storage duration, cold chain integrity, packaging type, gas composition, and additional antimicrobial barriers. Therefore, modern storage conditions should be viewed as a means of not only extending shelf life, but also as a tool for managing the microbiological safety of these materials.

A review of the literature has shown that maintaining a stable temperature is essential for preserving appropriate microbiological parameters. Kukhtin and Salata (2023), Doulgeraki et al. (2012), and Pelykh, Konoplianko and Vinnyk (2024) demonstrated that, even during refrigerated storage, the intensity of microbiological processes in meat raw materials decreases but does not cease. The level of microbial contamination depends on initial contamination, water activity, pH, oxygen availability, and storage duration. Pelykh, Konoplianko and Vinnyk (2024) established that during conventional cooling, the total microbial count gradually increases, the dominant microbiota composition changes, and the sanitary and microbiological characteristics of the raw materials deteriorate. This directly affects their safety and technological suitability.

Separate studies have shown that failure to comply with storage conditions or a break in the cold chain accelerates the growth of spoilage microflora and microorganisms of safety concern. Kukhtin and Salata (2023), Doulgeraki et al. (2012), and Necidová et al. (2024) have demonstrated that temperature fluctuations and inadequate storage condition control lead to an increase in psychrotrophic aerobic microflora populations, including *Pseudomonas* spp., *Brochothrix thermosphacta*, certain Enterobacteriaceae, lactic acid bacteria, yeasts, and microscopic fungi. The specific microorganisms present depend on the packaging type and gas atmosphere composition.

Concurrently, the survival and growth risk of indicator and potentially pathogenic microorganisms, including *Salmonella* spp., *Listeria monocytogenes*, *Escherichia coli*, and *Staphylococcus aureus*, increases. Therefore, violations of temperature control should be considered not only a factor that accelerates spoilage, but also one of the leading causes of deterioration in the microbiological safety indicators of raw materials of animal origin.

The results of studies on the consequences of a break in the cold chain are particularly noteworthy. [Necidová et al. \(2024\)](#) and [Pelykh, Konoplianko and Vinnyk \(2024\)](#) have established that even a brief deviation from the optimal storage temperature alters the microbiological profile of chilled poultry meat, promotes more intensive microbial growth, and reduces the effectiveness of packaging systems. A synthesis of these data provides grounds for asserting that temperature stability is an essential prerequisite for realizing the positive effects of any innovative storage technologies ([Fig. 1](#)).

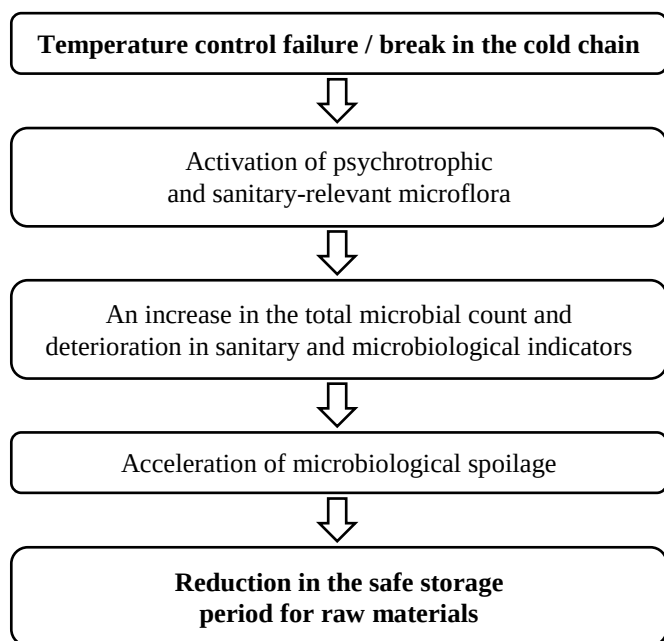


Figure 1. Generalized diagram of changes in microbiological parameters of raw animal products when storage conditions are not maintained.

[Sai-Ut et al. \(2025\)](#) demonstrated that elevated CO₂ levels have a pronounced bacteriostatic effect. This effect reduces microbial contamination of raw materials and slows the growth of spoilage microorganisms. Meanwhile, [Heir et al. \(2022\)](#) found that the effectiveness of a modified gas atmosphere depends on the initial microbial load, the type of meat, temperature stability, and the proper selection of gases in the packaging system.

The literature review highlights active packaging and edible coatings as one of the most promising areas for the innovative storage of animal-derived raw materials. [Bhat](#)

[et al. \(2024\)](#) and [Heir et al. \(2022\)](#) have demonstrated that functionalized packaging systems incorporating organic acids, such as caprylic acid, essential oils, postbiotics, menthol, alginates, and other polysaccharide components, not only mechanically isolate raw materials from external environments but also actively influence the product's surface microflora. Additionally, [Ranjbar et al. \(2025\)](#) and [Abbasi et al. \(2023\)](#) have found that using these systems results in a reduction of the total microbial count and inhibits the growth of spoilage microorganisms, including *Pseudomonas* spp., yeasts, and molds. In some instances, these systems can also help control contamination by *Salmonella* spp. and other pathogens. Therefore, active packaging should be considered a highly innovative approach to ensuring the microbiological safety of raw materials of animal origin.

Edible coatings have gained significant attention in both scientific research and practical applications due to their ability to simultaneously provide a barrier effect and a localized antimicrobial effect. [Bhat et al. \(2024\)](#) and [Ranjbar et al. \(2025\)](#) have shown that coatings made from alginates, plant polysaccharides, essential oils, and postbiotics can effectively extend the shelf life of chicken and lamb when stored under refrigeration. These coatings inhibit the growth of spoilage microorganisms and help maintain stable microbiological parameters throughout the storage period. As a result, edible coatings are regarded as a promising component of modern controlled microbiological systems.

Data on combined barrier technologies constitute a separate group of results. A review of the literature has shown that combining several antimicrobial agents provides a significantly greater effect compared to using a single preservation method. [Qiu et al. \(2025\)](#), [Oliinychenko, Tiwari and Stratakos \(2026\)](#), and [Oyewole, Izuafa and Ayomide \(2026\)](#) have demonstrated that the combined use of cold plasma, organic acids, nanoemulsions, preservatives, and acid salts allows for more effective inhibition of *Salmonella* Typhimurium, *Listeria monocytogenes*, and other microorganisms relevant to the safety of raw meat. This approach is consistent with the modern concept of multi-barrier preservation, in which the combined action of several moderate factors provides a more profound antimicrobial effect than a single isolated factor.

Modifications to barrier technologies in meat storage may include several approaches, such as combining refrigeration with modified atmosphere packaging (MAP) or vacuum packaging. Other methods involve using active films that incorporate organic acids, applying edible coatings with essential oils or postbiotics, and integrating cold plasma, nanoemulsions, and naturally derived preservatives. An analysis by [Qiu et al. \(2025\)](#), [Oliinychenko, Tiwari and Stratakos \(2026\)](#), and [Oyewole, Izuafa and Ayomide \(2026\)](#) indicates that these combined methods show the greatest potential for controlling *Salmonella* Typhimurium, *Listeria monocytogenes*, and other microorganisms that pose risks to the safety of raw meat.

The essence of barrier technologies lies in creating a set of interrelated limiting factors that simultaneously affect various life processes of microorganisms. A temperature barrier reduces the rate of enzymatic and metabolic processes; a gas barrier, caused by elevated CO₂ or reduced O₂, limits the growth of aerobic microflora; a chemical barrier alters the pH, redox potential, or availability of nutrient substrates; the physical barrier reduces the raw material's contact with oxygen and the external environment; the biological barrier is associated with the action of postbiotics, bacteriocins, or microbial metabolites; the nanostructured barrier ensures the controlled release of active substances onto the product's surface. The main modifications of barrier technologies include: cooling combined with vacuum packaging; MAP with an increased CO₂ content;

MAP following treatment with organic acids or their salts; active films containing caprylic acid, diacetyl, or essential oils; edible polysaccharide coatings with postbiotics; nano coatings based on alginates or other biopolymers; and the combination of cold plasma with organic acids and nano emulsions. These modifications are innovative because they combine several barriers to reduce the microbial load while minimizing the thermal and chemical impact on the raw materials. A literature review enabled us to classify innovative preservation methods based on their mechanisms of action. It also provided a summary of specific quantitative indicators demonstrating the effectiveness of these methods in inhibiting microbial growth, reducing pathogen contamination, and extending the safe shelf life of animal-derived raw materials (Table 1).

Table 1 — Innovative methods for storing animal-based raw materials: advantages, disadvantages, and impact on microbiological safety parameters

Storage method	Object	Primary microbiological effect	Advantages	Disadvantages
Cold chain disruption (negative control scenario)	Chilled chicken	Deterioration in APC, PMC, and fecal indicator parameters	It makes it possible to clearly demonstrate the critical role of temperature stability	This is not an improvement; it reflects a negative scenario
MAP with elevated CO ₂	Pork cutlets	Inhibition of bacterial growth and TVB-N, extension of shelf life	Extended shelf life while maintaining acceptable quality	Requires precise selection of the gas mixture; excess CO ₂ may accelerate oxidation
High CO ₂ in Hi-O ₂ MAP	Goat meat	Inhibition of TVC and stabilization of the microbial profile	Effective control of spoilage microorganisms	Color quality may deteriorate at high CO ₂ levels
Organic acids / salts and MA	Chicken	Initial reduction of microbial load and slowing of subsequent growth	Significant effect when combined with MA	The effect depends on salt concentration, pH, and storage conditions
Edible MSM coating and postbiotic	Lamb	Reduction of microbial growth and stabilization of quality	Natural system, normal microbial flora	The optimal concentration of the postbiotic must be determined
AlgNP coating with menthol and <i>Zataria multiflora</i> EO	Chicken thighs	Inhibition of spoilage microorganisms (<i>Pseudomonas</i> , yeasts/molds) and extension of shelf life	Environmentally friendly, combining barrier and antimicrobial effects	The microbiological effect depends on the coating composition
PLA film with caprylic acid	Chicken and beef	Pronounced anti- <i>Salmonella</i> effect	Active packaging without compromising color or texture	Technological adaptation of the film is required for production
Diacetyl-based active sachets	Beef	Reduction in levels of spoilage microorganisms <i>Salmonella enterica</i> and <i>Pseudomonas</i> spp.	Contactless active packaging, high efficiency	Greater technological complexity and the need for validation

To clarify the comparative effects of preservation methods, this study summarized literature data on the duration of safe or microbiologically stable storage of meat raw materials in the analyzed studies. The comparison shows that, while cooling primarily serves an inhibitory function, innovative storage regimes extend the duration of microbiological stability by combining temperature, gas, packaging and antimicrobial barriers (Table 2).

The results of the analysis show that innovative storage methods are an effective way of managing the microbiological safety of raw materials of animal origin. Systems that combine a stable temperature regime, gas atmosphere modification, active packaging and additional antimicrobial barriers offer the greatest practical potential. However, even the most advanced technological solutions are ineffective if the cold chain is broken, since temperature instability is one of the main

factors contributing to the deterioration of the microbiological condition of raw materials. From the perspective of ISO 22000:2018 (ISO, 2018), such protocols can be considered prerequisite programs or control measures relating to hazard analysis, temperature

monitoring, traceability, and corrective actions. From the perspective of ISO 9001:2015 (ISO, 2015), their implementation aligns with a process-based approach, risk management, documented procedures, and decision-making based on factual data.

Table 2 — A comparative analysis of the shelf life of raw meat products depending on the method of preservation or storage

Storage method	Object and conditions	Estimated duration	Microbiological stability criterion	Conclusion on innovation
Traditional refrigerated storage without an additional barrier	Raw meat products at cooling temperatures	Short-term storage; the safe period is shortened by temperature fluctuations	Gradual increase in total microbial count	The method is basic but not innovative; its effect is limited to slowing the growth of microflora
Cold chain disruption	Chilled chicken; simulation of temperature deviations from the recommended conditions	The safe period is effectively reduced because even a brief rise in temperature stimulates microbial growth	Deterioration of APC, PMC, and fecal indicator parameters	Negative control scenario; confirms that no innovative packaging can compensate for the loss of temperature stability
MAP with elevated CO ₂	Pork cutlets, stored at 4 °C	In the study by Liang et al. (2024), the stability of quality and microbiological parameters was maintained for more than 16 days	Inhibition of bacterial growth	The innovation lies in controlling the gas composition of the environment; the method is more effective than simple cooling
Hi-O ₂ MAP with elevated CO ₂	Goat meat during cold storage	The evaluation period covered extended refrigerated storage; higher CO ₂ levels stabilized the microbial profile throughout the study	Lower TVC, control of <i>Pseudomonas</i> spp. and spoilage microbiota	The method is suitable for raw materials where it is necessary to combine control of color and microbial growth
Organic acids or salts in combination with MA/MAP	Chicken after treatment with organic acids or acid salts	Potential extension of shelf life compared to the untreated control	Initial reduction in bacterial load and slower subsequent growth of microflora	The barrier is formed through a combination of chemical action and the gas environment; effectiveness depends on pH, concentration, and temperature
Edible MSM coating with a postbiotic	Lamb, 10 days at 4 °C	According to Abbasi et al. (2023), the coating extended the shelf life by more than 10 days	Reduction in microbial growth, stabilization of pH, moisture content, and sensory characteristics	The innovation relates to the biopolymer barrier and biologically active postbiotic components
AlgNP coating with menthol and Zataria multiflora EO	Chicken thighs during cold storage	In the study by Ranjbar et al. (2025), microbiological changes were evaluated over 16 days	Lowest levels of <i>Pseudomonas</i> spp., aerobic mesophilic microflora, yeasts, and molds	The nanostructured edible coating ensures a more controlled action of active substances on the surface of the raw materials

Table 2 — continuation

Storage method	Object and conditions	Estimated duration	Microbiological stability criterion	Conclusion on innovation
Diacetyl-active sachets	Beef in a packaging system without direct contact between the active agent and the product	According to Rupérez, Nerín and Silva (2025) , after 11 days at 4 °C, inhibition of <i>Salmonella enterica</i> was approximately 77%, and that of <i>Pseudomonas</i> spp. and lactic acid bacteria was over 90%	Control of pathogenic and spoilage microflora	The method is innovative due to its contactless active packaging and controlled release of the antimicrobial component
Combined barrier technologies	Combination of cooling, MAP, active packaging, edible coatings, organic acids, postbiotics, or cold plasma	Depending on the system's composition, it provides the longest period of microbiological stability among the compared approaches	Simultaneous inhibition of psychrotrophic, aerobic, and opportunistic microflora	This is the most well-founded innovative direction, as it combines several control mechanisms and offers the highest practical potential

Discussion. The study found that maintaining the appropriate temperature is key to microbiological stability. This is consistent with the findings of [Necidová et al. \(2024\)](#), [Pelykh, Konoplianko and Vinnyk \(2024\)](#), and [Doulgeraki et al. \(2012\)](#), who demonstrated that the growth of psychrotrophic microflora in raw meat does not cease under refrigerated conditions, but merely slows down. Therefore, traditional refrigerated storage should be considered a necessary but insufficient measure for ensuring safety. The correlation between temperature instability and deterioration of sanitary and microbiological characteristics indicates that breaking the cold chain negates the effectiveness of modern packaging technologies and creates conditions that activate spoilage microflora and pathogens.

Notably, the material under review reveals a clear shift in approaches to assessing microbiological risks. While traditional studies focused primarily on total microbial counts and spoilage indicators, recent works by [Her, Han and Ha \(2024\)](#) and [Oliynychenko, Tiwari and Stratakis \(2026\)](#) examine storage conditions in terms of controlling specific, pathogen-related microorganisms, such as *Salmonella* spp., *Listeria monocytogenes*, *Escherichia coli*, and *Staphylococcus aureus*. Given this shift in focus, it can be argued that the concept of safe storage today encompasses more than just preventing spoilage; it also involves the targeted control of microbiological hazards that could endanger consumer health.

This enables us to interpret the study results from the perspective of the multi-barrier concept. According to this concept, the most effective way to control the growth of opportunistic and pathogenic microorganisms is through the combined action of several moderate factors. In our opinion, this model is the most promising for the practical storage of animal-derived raw materials as it

enables the simultaneous addressing of safety, quality, and shelf-life extension issues.

However, the analysis showed that innovative storage regimes cannot be considered universal or equally effective for all types of animal-derived raw materials. Studies by [Qiu et al. \(2025\)](#) and [Liang et al. \(2024\)](#) have shown that the strength of their antimicrobial effect depends on the type of meat, its physicochemical properties, the initial contamination level, the dominant microbiota, and the preliminary processing conditions. Therefore, the practical implementation of innovative storage methods should be based on a differentiated approach, whereby the choice of packaging or antimicrobial system takes into account the specific characteristics of a particular type of raw material rather than solely considering the method's general technological advantages.

Another important finding that emerges from the analyzed material is that modern, innovative approaches are transforming the concept of storage within the technological chain. While storage was previously considered a passive process aimed at slowing down natural spoilage, it is now increasingly being recognised as a controlled microbiological process. [Pivovarov, Kovalova and Koshulko \(2025\)](#) and [Bhat et al. \(2024\)](#) have demonstrated that, under the right conditions, the composition of the microbiota can be altered, the growth of spoilage microorganisms can be inhibited, and raw materials can be kept safe for longer by using temperature, gas environment, packaging material structure, and antimicrobial agents.

Innovative storage methods must comply with the requirements of the management systems used in Ukraine. According to ISO 22000:2018 ([ISO, 2018](#)), the following elements must be included in the system for hazard analysis, monitoring, and corrective actions:

temperature control; gas atmosphere control; the sanitary condition of packaging; validation of antimicrobial barriers; and batch traceability. Similarly, under ISO 9001:2015 (ISO, 2015), these elements ensure process controllability, consistent quality, documented staff accountability, and the evaluation of implemented technology effectiveness. Therefore, innovative storage regimes must be evaluated based not only on their microbiological effectiveness, but also on the feasibility of their standardized implementation into the production system.

Conclusions. A review of the literature suggests that innovative storage methods are one of the key factors in ensuring the microbiological safety of raw materials of animal origin. The combination of controlled temperature conditions, modified gas atmospheres, active packaging, edible coatings, and combined antimicrobial technologies has been shown to inhibit the growth of spoilage microorganisms, reduce the risk of contamination, and extend the safe storage period of raw materials.

A comparative analysis of shelf life showed that innovative methods are advantageous when extending

shelf life involves simultaneous control of microbiological, chemical, and sensory parameters. Combined barrier technologies are the most promising based on these criteria, as they inhibit microbial growth through several mechanisms and can be adapted to specific types of raw meat.

Innovative storage methods should be implemented as part of a systematic approach to managing the safety and quality of food products. Within the framework of ISO 22000:2018 (ISO, 2018), these methods can serve as control measures or prerequisite programs. Within the framework of ISO 9001:2015 (ISO, 2015), however, they must be described as controlled processes with defined monitoring parameters, responsible personnel, records, and corrective actions.

Therefore, innovative storage methods should be viewed as an effective tool for the targeted management of the microbiological safety of raw materials of animal origin. Their practical application should be adapted to the type of raw material and the conditions under which it is handled.

Declaration of competing interest. The authors declare that they have no conflict of interest.

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