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Modern methods of raw meat processing to reduce microbial contamination

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Abstract. There are various methods to preserve the quality and extend the expiration date of food products. Raw meat from different animal species is a highly perishable product. The relevance of this research is driven by the need to summarise contemporary knowledge on approaches and

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techniques aimed at extending the storage duration of safe and high-quality meat, alongside their scientific justification. This article focused on finding means to reduce bacterial contamination, as microorganisms are the primary cause of meat spoilage. This study aimed to identify the most promising and optimal methods for extending the freshness of raw meat. To conduct the analysis, information from scientific primary sources, and electronic resources was used, and the results of experimental data on the application of scientifically based safe approaches were studied. A review of the main methods and measures aimed at extending the storage period of raw meat was carried out. The advantages and disadvantages of various methods of raw meat processing that have a bactericidal or bacteriostatic effect on various, including pathogenic, microorganisms that not only cause meat spoilage but can also be a danger to the potential consumer were established. Various traditional, novel, and innovative methods are currently employed in meat processing. Given the advancements in science and technology, a comprehensive approach to raw meat processing is emerging as the most promising. After analysing the research findings of numerous scientists, it has been concluded that biological technologies utilising lactic acid bacteria, combined with traditional physical methods such as refrigeration, offer the most optimal solution. This approach preserves the freshness of meat while minimising the impact on organoleptic properties, provided that temperature regimes and processing technologies involving cultures of lactic acid microorganisms are adhered to. The practical significance of this study lies in identifying the most promising directions for further research and improving existing safe antimicrobial treatments, particularly through the use of various strains of lactic acid starters. Their practical application will enable the preservation of meat freshness and extend its storage life

Keywords: slaughter products; lactic acid bacteria; disinfection with antimicrobial additives; quality and safety control; antimicrobial chemical substances

Introduction

Producing safe, high-quality food products is one of the primary and most important tasks of the agro-industrial sector in Ukraine and globally. Today, the issue of food safety is critically pressing, and there is a need to further research the justification and application of modern approaches used by the European Union. Modern retail trends and developments, driven by the demands of the food industry, are focused on extending the storage life of meat. Slaughter facilities play a pivotal role in supplying the population with high-quality, fresh, and safe meat products. This is achieved through the use of appropriate equipment, stunning methods, hygienic primary processing, and the implementation of specific measures designed to minimise bacterial contamination of half-carcasses and facilitate the subsequent storage of raw meat.

F. Leroy *et al.* (2023) highlighted in their study that raw meat is a complex, biologically active product undergoing numerous physicochemical and biochemical processes. Simultaneously, it is a valuable food source, rich in essential amino acids, fatty acids, and various bioactive compounds with health-promoting properties (e.g., taurine, carnosine), as well as easily absorbable micronutrients, often providing adequate nutrition for a wide range of consumers. According to European legislation, meat refers to muscle tissue and associated tissues obtained from the carcasses of domestic ungulates, including pigs, cattle, sheep, goats, domestic one-hoofed, as well as poultry, lagomorphs, and wild game animals (Regulation EC No. 853/2004, 2004).

Ukrainian researchers have investigated a promising method of treating meat with lactic acid bacteria cultures. They have demonstrated a reduction in microbial contamination of meat, allowing for an extended shelf life of pork half-carcasses under refrigeration (Vovkotrub *et al.,* 2023).

Meat quality refers to the degree of properties that characterise its nutritional, biological, and energy value, as well as its organoleptic, physico-chemical, biochemical, and other attributes that meet consumer needs. While meat quality can be assessed using various methods, safety and sensory attributes are paramount for consumers. These components are influenced by a range of internal and external factors, including animal genetics, production systems, feeding, pre-slaughter preparation, stress during slaughter, and post-slaughter carcass handling. Moreover, M. Gagaoua *et al.* (2022) and V.Z. Trokhymenko *et al.* (2023) emphasised the importance of the economic aspect of food production, which is ensured by rational primary processing methods and the subsequent utilisation of raw materials.

V. Kurcubic *et al.* (2022) highlighted that meat processing facilities employ a significant number of technologies aimed at enhancing the quality of the final product. Particular attention is paid to the method and speed of animal slaughter, as well as subsequent carcass chilling and storage. Furthermore, there has been a growing demand in recent years for safe and high-quality meat that contains only natural ingredients to extend its shelf life. Products should include natural food preservatives, such as organic acids and antimicrobial agents, which do not have adverse effects on human health.

Despite significant scientific advancements, there remains a need for more detailed research and in-depth study of the impact of primary processing of carcasses from livestock and poultry on the safety, quality, and marketability of meat. This research aimed to review modern methods and analyse the most promising approaches used to extend the shelf life of raw meat and to formulate recommendations for their practical implementation in production. The literature search utilised scientific databases such as Scopus, Web of Science, and other electronic resources, which provided information on meat processing methods, references to legal frameworks, and food legislation. Both Ukrainian and international research data were consulted. A thorough analysis of existing findings and studies in this field was conducted, followed by the systematisation of the available information. Traditional as well as new and innovative processing methods were examined. Given the importance of ensuring safe food products and the development of modern technologies, preference was given to the most up-to-date sources of information.

Cooling and freezing of farm animal carcasses

Cooling and freezing of agricultural animal carcasses are the most common traditional methods of meat preservation. Cooling extends the shelf life of meat by slowing down the growth of microorganisms and the chemical reactions that lead to spoilage. Another technique, freezing, primarily employs temperatures of -8°C and below.

H.E. Rojas *et al.* (2022) pointed out that, as global trade expands and the distance between producer and consumer increases, the demand for cooled and frozen meat is rising. This is due to the need to satisfy consumer expectations for longer product freshness, while also facilitating logistics and enhancing marketing. In recent years, research on the cooling of pork half-carcasses has focused on accelerated cooling to minimise microbial contamination and weight loss through evaporation. Additionally, accelerated cooling can also improve the physicochemical and biochemical properties of meat by reducing the post-slaughter metabolic rate.

Pork displaying signs of PSE (pale, soft, exudative) is frequently encountered. Typically, such animals have been raised using intensive feeding practices and restricted movement during their confinement. PSE characteristics are also observed in stress-sensitive animals, which can be caused by improperly conducted stunning, prolonged transportation, exposure to high temperatures, lack of oxygen, and so forth. A delay in the onset of cooling and insufficiently low cooling temperatures contribute to a decrease in pH levels. This defect is particularly pronounced in light-coloured muscle fibres. The meat produced from these animals has lower technological and commercial value. During freezing and thawing, a significant amount of fluid is released, and substantial mass losses occur during storage, boiling, or frying; moreover, when salted, the meat retains its pale colour. It is important to note that the light colour of the meat is attributed to a sharp decrease in pH levels following slaughter, facilitated by enzymes that more rapidly break down glycogen into lactic acid. This results in earlier post-mortem rigour, while the temperature of the carcass remains high, promoting the rapid denaturation of muscle proteins due to the action of proteases (Trevisan & Brum, 2020). Consequently, as noted by A. Rybarczyk *et al.* (2015), the meat assumes a lighter colour.

The DCB (dark cutting beef) defect primarily occurs in steers and rarely in heifers. The discolouration arises from prolonged pre-slaughter stress and the depletion of glycogen reserves. Additionally, a stress factor can lead to another meat defect, characterised by the presence of DFD (dark, firm, dry) attributes, most commonly observed in the carcasses of cattle and sheep, and less frequently in pigs and turkeys. This defect occurs when, as a result of stress, strenuous physical exertion, fatigue, or exhaustion, the glycogen content in muscle tissue decreases before slaughter, leading to an increase in pH due to reduced post-mortem glycolysis and resulting in rapid post-mortem rigour. H.E. Rojas *et al.* (2022) noted that the pH of such meat is typically greater than 6.2. These characteristics indicate that the carcass originated from an animal that experienced pre-slaughter stress, possibly due to injury or illness. Such meat has high water-binding capacity, a dark red colour, coarse fibrousness, a tough texture, increased stickiness, and poor storage stability.

Consequently, in animals that have experienced acute and short-term stress, the carcass may exhibit PSE characteristics due to protein denaturation, which contributes to a decrease in water-holding capacity, displacement of intracellular water and myoglobin into interfibrillar spaces, and softening of the muscle structure. If the animal has undergone prolonged pre-slaughter stress, the pH value increases as a result of low energy reserves in the muscles, the muscle tissue structure becomes denser and firmer, and the meat acquires DFD characteristics.

Therefore, the post-mortem changes that occur during the process of transforming the muscles of slaughtered animals into meat play a crucial role in the development of quality attributes and the overall perception of the fresh product. S.K. Matarneh *et al.* (2017) emphasised that after an animal is slaughtered, the supply of oxygen ceases, and glycogen with phosphate compounds is mobilised to maintain homeostasis through the synthesis of adenosine triphosphate. As a result of lactate formation, the pH level decreases. Subsequently, post-mortem rigour develops. With the inactivation of enzymes, metabolism ceases, and ATP, which provides the elasticity of muscle fibres, is depleted. This is followed by the proteolytic breakdown of structural proteins in the muscles, resulting in an enhancement of the meat's flavour properties.

H.E. Rojas *et al.* (2022) noted that the cooling process does not improve meat quality but merely maintains it, and therefore the meat must be of a satisfactory sanitary and hygienic standard. A safe cooling temperature is considered to be 4°C or below to inhibit the growth of microorganisms. This method is one of the most common in industrial settings. The biggest drawback of this method is the weight loss of the carcass due to the evaporation of water from the meat surface, which depends on the rate of temperature decrease. Consequently, when the cooling rate is lower, the weight loss increases.

Freezing is also a widely used method for preserving meat from various types of animals. This method is economically significant for the industry as it facilitates the trade of meat and logistical connections through extended storage periods. The primary objective of freezing is to maximise the retention of the meat's original properties, which requires careful control over the reduction of temperature and the crystallisation of liquids during the storage of carcasses in a frozen state, as well as during their thawing process. When meat is frozen, most of the water solidifies and forms ice crystals, which is accompanied by the separation of dissolved solids. Rapid freezing results in the formation of small ice crystals that generally remain within the muscle tissue, thereby preserving its microstructure. During the thawing process, the liquid is released and bound to proteins. If freezing occurs quickly while thawing is slow, moisture loss is minimised. However, during the storage of meat in a frozen state, ice crystals grow and damage muscle cells, which, in turn, leads to the release of enzymes that contribute to the oxidation of proteins and lipids. This process can, as noted by V. Lebret & M. Candek-Potokar (2022), lead to a deterioration of flavour, changes in colour, and alterations in texture.

Rapidly reducing the temperature of muscles before they reach the appropriate level of acidification can lead to carcass shrinkage (weight loss). Shrinkage is particularly evident in carcasses from animals with lower levels of subcutaneous fat, which facilitates faster heat loss. Shock cooling also contributes to the freezing of the skin and muscles located directly beneath the skin. During thawing, this leads to the leaching of adjacent tissue and undesirable meat colour. In studies by A. Rybarczyk *et al.* (2015), it was shown that shock cooling of meat had a negative impact on organoleptic characteristics such as tenderness and flavour. However, the results of their study did not reveal any significant differences between the effects of shock cooling and conventional cooling systems on meat quality between pig exterior classes.

The well-known Rinse&Chill (RCT) technology involves washing the vascular system of various types of animals after slaughter using a chilled isotonic solution at a temperature of +3°C. This solution contains 98.5% water along with a mixture of dextrose, maltose, and sodium phosphate (Hwang *et al.,* 2022). Additionally, an isotonic solution at +14°C is used, which comprises 98.5% water and a mixture of glucose, polyphosphates, and maltose (Fowler *et al.,* 2017).

According to research by S.V. Erazo-Castrejon *et al.* (2019), which determined the haemoglobin content in muscle extracts as a measure of blood removal, the application of the RCT method ensures the removal of 40% more blood from the muscles compared to conventional methods, which leave approximately 60% of blood in the muscles of pigs. This technology effectively removes residual blood from the carcass, rapidly lowers the internal temperature of the muscles, and optimises the reduction of pH by delivering glycolytic substrates in the wash solution.

Research on the Rinse&Chill (RCT) technology has shown that early post-mortem washing of the blood vessels in beef carcasses positively impacts the quality and safety of the meat, as well as its shelf life and the safety of meat products (Hwang *et al.,* 2022). This procedure facilitates the washing away of residual blood from both beef and pork carcasses. The use of pre-chilled isotonic solutions for intact animal carcasses ensures a rapid reduction in the internal temperature of the muscles and accelerates the cooling of the entire carcass. This technology, in particular, contributes to a decrease in pH and ensures effective cooling of the carcass, thereby improving the quality and safety of the meat. The isotonic RCT solution contains substrates that permeate the muscles, which remain physiologically active during the early post-mortem vascular washing. As a result, they are fully metabolised by the muscles and leave no residues. This technology has been commercially approved and has been in continuous use in the United States since 2000 and in Australia since 1997. As of January 2022, 23 meat processing enterprises in five countries (Australia, the USA, Canada, New Zealand, and Japan) have implemented this technology, all of which have assessed and approved the RCT. K. Hwang *et al.* (2022) noted that these enterprises operate under standard sanitation operating procedures (SSOP) and a Hazard Analysis Critical Control Point (HACCP) system.

Therefore, to effectively cool pork carcasses in meat processing plants, various methods are employed, often in combination with pre-slaughter preparation techniques and animal stunning methods.

Chemical technologies for meat processing

M. Lulietto *et al.* (2015) noted that meat is a unique nutrient-rich food but can pose a risk when contaminated with and reproduction of pathogenic microorganisms in it. To reduce microbial contamination of meat, particularly animal carcasses post-slaughter, chemical treatments are employed. The European Food Safety Authority (EFSA) has issued guidelines outlining the essential components and prerequisites that studies must include demonstrating that a substance intended for use to remove microbial surface contamination from food of animal origin will not pose any significant risk to consumer health and will contribute to a significant reduction in the prevalence and number of pathogenic bacteria, thereby reducing the microbiological risk. Given such regulations, an increasing number of new products are seeking to enter the European Union market. These are primarily foods produced using new technologies, derived from novel sources, or containing novel substances. Additionally, traditional foods consumed in non-EU countries and not consumed in the EU before 15 May 1997 are also considered "novel foods" according to Regulation (EU) No. 2015/2283, 2015. E. Ververis *et al.* (2020) emphasised that food business operators wishing to market such products in the European Union must obtain authorisation from the European Commission.

Scientific research conducted by Z.A. Ellatif *et al.* (2020) and Z. Kaplan *et al.* (2021) has demonstrated that a significant number of chemical components, including organic acids, have been developed and used to reduce contamination of slaughtered animal meat and extend its shelf life. At the same time, D.N.N. Madushanka *et al.* (2018) and O.B. Braiek & S. Smaoui (2021) noted that treatment with solutions of organic acids, such as lactic and acetic acid at concentrations of 1-2%, is also effective in reducing bacterial contamination, but higher concentrations of these acids cause the carcasses to whiten.

H. Van Ba *et al.* (2019) conducted a study using 3% acetic and lactic acid solutions to reduce bacterial contamination on beef carcasses. Live animals were sprayed with the acid solution on their skin, and carcasses were sprayed immediately after slaughter. Identified microorganisms were identified through sequencing. Various microorganisms, such as *Staphylococcus, Shigella, Bacillus, Escherichia,* and *Salmonella*, were localised on the outer skin surface of live animals and the surface of their carcasses. Disinfectant sprays significantly reduced the number of all the aforementioned bacteria on the carcass skin surface compared to the control group without spraying. Thus, the spraying method can be recommended to reduce cross-contamination of beef carcasses without negatively affecting meat quality.

A similar study was conducted to detect and identify microbial populations on pork carcasses at various stages of slaughter and on pork cuts 24 hours post-slaughter, as well as to evaluate the effectiveness of sprays containing different concentrations (2% and 4%) of lactic acid. The spray was applied to the carcass surface at the end of the slaughter line. Bacterial genus identification, including *Staphylococcus, Salmonella, Shigella*, *Enterococcus, Escherichia, Acinetobacter* and *Corynebacterium* spp., was carried out. Their counts ranged from 2.70 to 4.91 log10 CFU/100 cm^2 on carcasses during slaughter. Most of these genera were also found on carcasses after 24-hour cooling. *Staphylococcus, Acinetobacter* and *Corynebacterium* were identified on cuts from untreated carcasses but were absent on treated ones. The bacterial count significantly decreased on carcasses and cuts treated with a lactic acid solution, particularly at the 4% concentration. Thus, according to H. Van Ba *et al.* (2019), spraying pig carcasses with a 4% lactic acid solution could be an effective method for reducing bacterial contamination, and enhancing the microbiological safety of pork.

In Brazil, the HACCP (Hazard Analysis and Critical Control Points) program was established by Circular No. 369 of June 2, 2003, issued by DCI/DIPOA (Control Division of International Trade/Department of Inspection Animal Products, Brazil). Common critical control points (CCPs) for slaughter are faeces, intestinal, and milk contamination of carcasses, with no tolerance limits for their presence. The same program recommends corrective actions for faecal contamination removal through trimming the contaminated part of the carcass and visual inspection. Under appropriate slaughter conditions, despite swine carcasses having satisfactory visual characteristics, they can be heavily contaminated, as their skin is a primary source of contamination. S. Bonardi (2017) noted that the stress factor associated with grouping, transportation, and holding animals at the slaughterhouse can provoke the excretion of *Salmonella* and other pathogens in latent carriers. This highlights the importance of adhering to good slaughter hygiene practices.

The study found that washing pig carcasses with water at a pressure of 8 bars can replace the method of cutting away contaminated parts without significantly affecting microbial contamination, while also reducing the risk of cross-contamination. J. Brustolin *et al.* (2014) found a decrease in the number of psychrophilic and mesophilic microorganisms on the surface of pig carcasses that were treated with steam and then irrigated with a 2% lactic acid solution.

For the treatment of pig carcasses, V. Silano *et al.* (2018) conducted a study using a 2-5% lactic acid solution in the form of an aerosol at temperatures up to 80°C. In this process, meat cuts pre-chilled by cold water showering were immersed in solutions at temperatures up to 40°C, with an optimal exposure time of up to 30 seconds. It was noted that exceeding the established concentration could, at least temporarily, change the appearance of meat cuts. The treatment of carcasses with organic acid solutions was allowed at any stage: both after bleeding the carcasses and immediately before packaging. Regarding the amount of solution, a sufficient amount to cover the entire surface of the carcass was used. Additional rinsing after treatment with lactic acid was not provided. On the contrary, the remaining organic acid suppressed the growth of microorganisms in case of repeated bacterial contamination.

Therefore, organic acids are the safest chemicals used to treat meat to extend the product's shelf life by killing or inhibiting the growth of pathogenic microorganisms. A. Morey *et al.* (2014) indicated that acids accumulate in the cytoplasm of microorganisms. This rapidly decreases the pH, disrupts optimal enzymatic activity, and negatively affects the synthesis of proteins, DNA, and RNA. Currently, lactic and acetic acids are the most widely used in the food industry. G.A.M. Rossi *et al.* (2023) highlighted the potential use of other acids, such as benzoic, ascorbic, citric, propionic, formic, succinic, and tartaric acids as food preservatives to increase the shelf life of meat.

M. Ciriaco *et al.* (2021) investigated the bacteriostatic effects of acetic and citric acids on *Salmonella*. To treat pig carcasses, 2% and 5% solutions of these acids were used. Both acids at the specified concentrations exhibited bacteriostatic activity. However, better results were obtained when treating pig carcasses with 5% lactic acid. In another study, S. Dan *et al.* (2017) investigated the effects of lactic, acetic, and citric acids at various concentrations (1%, 2%, 3%) on bacterial strains of *Salmonella enteritidis, Escherichia coli* and *Listeria monocytogenes* when treating beef. The researchers noted that among these organic acids, a 3% solution of lactic acid was the most effective, while acetic and citric acids showed slightly lower effectiveness. In the food industry, malic and tartaric acids are also allowed to be used, but these acids are less effective when treating carcasses.

It is important to remember that the effectiveness of carcass surface treatment depends not only on the choice of a specific organic acid but also on the water pressure, its temperature, and the duration of the treatment. J.H. Park *et al.* (2005) recommended using low-pressure hot water washing or immersion, as well as high-pressure spraying, with an average treatment time of 10 to 20 seconds. Thus, there is currently a wide range of antimicrobial measures, such as carcass washing, treatment with organic acids, trimming, and deburring with a knife, etc. However, intestinal pathogens, especially *Escherichia coli* and *Salmonella*, remain a major problem for the safety of meat products, including beef. Currently, none of the methods is sufficiently effective for these pathogens when treating carcasses. C. Kocharunchitt *et al.* (2019) noted that during the study of antimicrobial agents, chlorine dioxide and peracetic acid showed good results when treating beef carcasses by spraying during cooling.

Chlorine is the most popular and widely used antimicrobial agent in poultry processing in the USA but is not permitted for use in the European Union (EU). M. Sohaib *et al.* (2016) noted that adding 18-25 mg/L to cold water could significantly reduce *Salmonella* counts. The effectiveness of chlorine increases proportionally with its concentration in the disinfectant solution. It should be noted that higher concentrations can affect the carcass colour and also contribute to the development of a specific odour.

The disinfection of animal carcasses with chlorine also has its advantages and disadvantages. Chlorine is widely used for the disinfection of animal products, particularly poultry. It is a relatively inexpensive chemical compound that is easy to apply to carcasses. It has high antimicrobial activity against both gram-positive and gram-negative microorganisms. The mechanism of action of chlorine involves the destruction of the bacterial cell wall due to its high oxidative potential. As noted by S. Sheen *et al.* (2011), chlorine solutions are effective even at low concentrations. M. Kumari & S.K. Gupta (2022) expressed concerns about the limitations of using chlorine, which is neutralised by organic matter, and recommended using it only after skinning to prevent neutralisation by organic matter on the carcass surface. In addition, chlorine is a toxic substance, its concentration must be carefully controlled, and when reacting with organic matter, it can form carcinogenic compounds – trihalomethanes, which pose a serious threat to human health.

It is important to note that the use of various chemicals, including chlorine, depends on geographic location and the subsequent marketing of finished products. K. Chousalkar *et al.* (2019) noted that in Australia and many Asian countries, chlorine remains the most common disinfectant for poultry meat. Compared to other disinfectants, it is cheaper and easier to use. A.R. McWhorter *et al.* (2023) indicated that Australia adheres to recommendations for the safe use of chlorine in the food industry, particularly the meat industry, where the concentration of this compound is not allowed to exceed 10 mg/L (ppm). In the USA, regulations allow a higher concentration – up to 20 mg/L for washing or spraying poultry carcasses, and up to 50 mg/L in cooling tanks.

S S.M.E. Rahman *et al.* (2013) noted that chemical treatment also includes ozone treatment, which is a water-soluble gas of natural origin that is a strong oxidant. This gas can attack the cell membrane of bacterial cells and also has antiviral effects. However, ozone also accelerates the oxidative spoilage of fats and affects muscle tissue, causing discolouration. Therefore, ozone is mainly used to treat empty freezers for meat storage.

Thus, the significant number of antimicrobial chemical agents designed to reduce contamination of animal carcasses after slaughter indicate their effectiveness but have several drawbacks, including deterioration of the commercial appearance of meat, toxicity to humans, and geographical restrictions. The search for safe and effective agents capable of ensuring long-term storage of meat and meat products continues.

Use of biological approaches to extend the shelf life of meat

In the food industry, the use of biological methods to extend the shelf life of raw meat is considered promising. Two main categories of biological agents have been used recently: starter cultures and protective cultures. Starter cultures are a type of microorganism used to initiate fermentation and produce specific chemicals that give fermented products their characteristic texture and flavour. V.P. Singh (2018) noted that protective probiotics are primarily used to manage antibacterial properties and minimise the persistence and growth of harmful microorganisms in food. Due to their non-toxic, non-immunogenic characteristics, thermal stability, and broad bactericidal activity, lactic acid bacteria serve as excellent biopreservatives. In addition to lactic acid bacteria, bacteriocins, bacteriophages, and bacteriophage-encoded enzymes are also used to ensure the quality and safety of food products.

Biological methods are gaining popularity due to their ecological approach. T. Bintsis (2018) established the safety of lactic acid bacteria (*LAB*) for food products, specifically *Lactococcus, Lactobacillus, Pediococcus, Leuconostoc, Streptococcus,* and *Enterococcus*, which can be added as starters to meat products. E.E. Imade *et al.* (2021) indicated that these microbial groups can inhibit the growth and activity of bacteria that spoil meat, providing an alternative to the use of chemical compounds. As the demand for high-quality food products free from synthetic chemicals increases –

driven by changes in lifestyle and consumer eating habits – lactic acid bacteria are increasingly utilised to extend the shelf life of fermented products. Their antimicrobial activity is attributed to metabolites such as lactic acid, hydrogen peroxide, and bacteriocins. S. Kaveh *et al.* (2022) demonstrated that *LAB* can inhibit pathogenic bacteria during the processing of raw meat and meat products. However, there are limitations to their use related to regulatory frameworks, the technology for applying different types of lactic acid microorganisms, and the need to consider factors such as storage time, temperature, and pH levels. Improper application can lead to spoilage of meat. The positive influence of *Lactobacillus sakei* on the cooling pork half-carcasses has been established. For instance, V. Vovkotrub *et al.* (2023) observed the preservation of transverse and longitudinal striations of muscle fibres during microscopic examination on the fourth day of storage, in contrast to untreated pork half-carcasses.

D.F. Benitez-Chao *et al.* (2021) and D. Bhattacharya *et al.* (2022) noted that bacteriocins are antimicrobial peptides produced by various bacterial strains. They can be added to raw or cooked meat to inhibit pathogenic microflora. The research demonstrated the ability of bacteriocins to suppress pathogenic microorganisms such as *E. coli, Salmonella,* and *Listeria*, highlighting the relevance and potential of these agents. The only commercially available bacteriocin is nisin, which is permitted for use in the food industry, particularly for the processing of meat and meat products. Y.B. DeMartinez *et al.* (2002) applied nisin and a spray of lactic acid (1.5%, at 25°C) to poultry and bovine carcasses to reduce the number of aerobic bacteria, *E. coli*, or coliforms. The use of nisin alone was found to have no effect on most gram-negative bacteria, including pathogenic strains. Combinations of various bacteriocins have improved the inhibition of foodborne pathogens. For example, sakacin G and sakacin P, produced by *L. sakei* CWBI-B1365 and *L. curvatus* CWBI-B28, respectively, showed positive results, with a noted suppression of the growth of *L. monocytogenes* in poultry and beef (Dortu *et al.,* 2008). A. Radaic *et al.* (2020) indicated that the semi-purified bacteriocin BacTN635, produced by *L. Plantarum* sp. TN635 and isolated from meat reduced the proliferation of *Listeria* and other spoilage microorganisms in beef and chicken breast under refrigeration conditions.

Bacteriophages are viruses that specifically infect bacteria and are generally considered harmless to humans, animals, and plants. Due to their strict host specificity, bacteriophages can infect and lyse only certain bacteria, or even only specific strains within a species. Bacteriophages do not have a negative impact on the environment. Numerous studies and examples have shown that bacteriophages can be effectively used to control pathogenic bacteria in food products. A. Ishaq *et al.* (2020) demonstrated that in a study on the effect of the bacteriophage *List-Shield* on reducing the number of *L. monocytogenes* in contaminated beef samples, pathogen growth continued on the surface of raw beef at a refrigerated temperature of 4±1°C. However, over a 15-day storage period of beef samples treated with bacteriophages, a significant reduction in pathogen concentration was observed. Additionally, bacteriophages had no negative impact on the colour or pH of the stored beef samples. This indicated that they can be used as an innovative antibacterial strategy to slow down the growth of pathogenic bacteria on the surface of meat.

Thus, lactic acid bacteria play a crucial role in preserving and extending the shelf life of meat and meat products by producing bacteriocins, organic acids, and other metabolites. The use of these agents necessitates further research, particularly the development of guidelines and regulations regarding their application as food additives in meat and meat products.

Innovative approaches to meat and meat product processing

Beyond traditional methods, novel and innovative technologies are employed to protect meat products from spoilage and extend their shelf life. As highlighted by W. Khalid *et al.* (2022), these include non-thermal processing technologies such as gamma irradiation, electron beam irradiation, high-pressure processing, and pulsed electric fields.

Irradiation is a process used to control foodborne pathogens, enhance the safety, and extend the shelf life of meat products by maintaining stable nutrient content during storage. This method is also considered an effective way to control microbial growth and eliminate microbiological hazards in meat and meat products. Currently, the irradiation of food products is regulated by national and international standards to ensure product safety. R. Indiarto *et al.* (2023) emphasise the need for labelling such products as "irradiated" and indicating the irradiation dose. In the United States, the Food Safety and Inspection Service (FSIS) of the USDA oversees the safety and labelling of meat, including the inspection and testing of irradiated products. T. Wahyono *et al.* (2024) pointed out the importance of adhering to the irradiation dose as it can have a negative impact on meat quality if not properly controlled.

According to the World Health Organization (WHO), irradiation doses below 10 kGy are generally considered safe and do not adversely affect the quality or safety of food products (Khalid *et al.,* 2022). Ionising radiation, when applied to food, minimises or completely eliminates pathogenic microorganisms that cause spoilage. G.M. Khalafalla *et al.* (2018) demonstrated the effectiveness of irradiation in extending the shelf life of minced meat, particularly beef. A. Amiri *et al.* (2019) indicated that this method is lethal to pathogenic microorganisms such as *Salmonella* and *Escherichia coli*, allowing for a significant extension of food shelf life. Additionally, studies have reported minimal impact of irradiation on the sensory properties and nutritional value of food (Lima *et al.,* 2018). Research also suggests that irradiation can be combined with other chemical substances and technologies to enhance the effectiveness of meat decontamination.

Ultrasonic technology involves the use of sound waves with frequencies between 20 and 100 kHz to damage the cell membranes and DNA of microorganisms (Morild *et al.,* 2011). This technology is particularly suitable for sanitising poultry carcasses, as it typically involves immersing the food product in an ultrasonic bath. Ultrasonic waves are safe and non-toxic to humans. A study combining the effects of ultrasound and lactic acid demonstrated a reduction in the number of gram-negative microorganisms in poultry meat.

Cold plasma is an innovative non-thermal food processing technology that employs energetic chemically reactive gases to inactivate unwanted microorganisms on meat, poultry, fruits, and vegetables. This flexible method, which exerts both bactericidal and bacteriostatic effects on microorganisms, relies on the use of electrical energy and carrier gases such as oxygen, nitrogen, or helium, without the need for antimicrobial chemical agents. The primary mechanism of action is associated with ultraviolet radiation and reactive chemical products generated during the ionisation process in cold plasma. A wide range of cold plasma systems is being developed, operating either at atmospheric pressure or in low-pressure processing chambers. B.A. Niemira (2012) noted that the bactericidal activity of cold plasma can reduce the colony counts of microorganisms by more than 5 logarithmic units for pathogens such as *Salmonella, Escherichiacoli O157:H7, Listeria monocytogenes* and *Staphylococcus aureus*. The effective processing time for food products using cold plasma can vary from 120 seconds to 3 seconds, depending on the type of food product and processing conditions.

P. Sammanee *et al.* (2022) and M. Gavahian & A.M. Khaneghah (2020) indicated that the method of immersion in cold liquid plasma can be employed to reduce the number of pathogenic microorganisms in pork and poultry meat with skin. This modern innovative technology holds potential for application in the meat industry during the slaughter of pigs and poultry. Liquid plasma contains ions, atoms, and molecules of oxygen, ozone, nitrates, and nitrites, and can generate reactive forms of oxygen and nitrogen that inactivate harmful microorganisms. Recent studies have demonstrated a reduction in the numbers of *S. enteritidis*, *S. typhimurium*, *E. coli* and *C. jejuni* on the surface of pork and poultry meat following 15 minutes of treatment with liquid plasma, evaluated on days 0, 3, 7, and 10. The effectiveness of reducing *S. Aureus* colonies in the meat was observed after a 3-day experiment. However, as noted by P. Sammanee *et al.* (2022), *P. aeruginosa* was not inactivated under the same experimental conditions. The results of the study established the efficacy of liquid plasma in reducing contamination by *Salmonella enteritidis, Salmonella typhimurium, E. coli*, *C. jejuni* and *S. aureus* on the surface of pork and poultry meat over a storage period of three days at temperatures between 4-6°C, with minimal organoleptic changes in the meat. During longer storage periods, a colour change was observed – pork samples took on a lighter hue, while less significant changes were noted in the poultry meat samples. A significant reduction in pH levels was found compared to the control group.

Innovative methods for meat processing include the application of pulsed electric fields (PEF). Despite the considerable number of scientific publications, this technology is still regarded as new in the food industry. The PEF technology is one of the promising non-thermal methods for preserving food products and can effectively manage biological hazards. Pulsed electric fields can be employed for the treatment of food items. K. Kopuk *et al.* (2020) noted that this method utilises short pulses of high voltage. V.R. Krishnamurthi *et al.* (2020) indicated that, under this method, the cell membranes of microorganisms are damaged due to the high voltage, leading to their death. While high voltage also generates heat, it does not adversely affect meat quality because of the extremely short exposure time. Some studies have reported contradictory findings regarding the use of pulsed electric fields for the decontamination of meat and meat products; therefore, further research is necessary to assess the potential of this method before its widespread application in the meat industry can commence.

Combined methods of processing meat and meat products

Currently, in addition to traditional methods such as cooling, pre-slaughter preparation, slaughter hygiene, and primary processing, various combined methods are employed to reduce the contamination of slaughter products by pathogenic microflora. Research findings indicate the individual and combined effects of organic acids, bacteriophages, and ultraviolet light on populations of *Salmonella* in beef mince contaminated with four strains of *Salmonella* bacteria, resulting in a contamination level of 3.5 log CFU/g after grinding. A.S. Danso *et al.* (2018) noted that the individual application of lactic and peracetic acids, or their combinations, did not result in a significant reduction in *Salmonella* numbers in beef mince. The individual use of bacteriophages and ultraviolet light reduced their numbers by 1 log CFU/g of mince. The combined application of bacteriophages and ultraviolet light resulted in a reduction of *Salmonella* in the mince by 2 log CFU/g.

F. Soyer *et al.* (2020) demonstrated that the application of activated lactoferrin and rosemary extract to pork meat effectively reduced levels of *E. coli, Salmonella* and *Listeria* in *in vitro* studies. However, further research is needed to investigate the synergistic effects of plant extracts and essential oils, as well as to determine optimal dosing and application conditions.

Ultrasonic technology has shown promise for the decontamination of poultry carcasses, as it involves complete immersion in an ultrasonic bath (Sohaib *et al.,* 2016). When combined with lactic acid, ultrasound has been shown to reduce the number of gram-negative bacteria in poultry meat. R.K. Morild *et al.* (2011) proposed a combined thermal (steam) and ultrasonic decontamination method for pork. This method effectively reduces the overall number of microorganisms, including *Salmonella* and *E. coli*. The advantage of this method is its short processing time and reduced water consumption; effective treatment can be achieved within 1-2 seconds without noticeable changes in the appearance of the pork.

S.K. Sadaghiani *et al.* (2019) established that to achieve a synergistic effect, rather than using *LAB* or bacteriocins separately, they should be combined with any natural antimicrobial substance. The scientists conducted a study using *Limosilactobacillus reuteri* and *L. plantarum* separately, as well as with 1% garlic extract in raw beef, which was stored for 12 days at 4°C. When *LAB* strains and garlic extract were used together, they reduced *L. monocytogenes* contamination to 1.5 log CFU/g, indicating a better effect with the synergistic action of the preparations. Thus, the combined use of measures, in particular, two or more, gives a better effect than a single intervention after the primary processing of animals. For carcass decontamination, preparations against pathogenic microorganisms and physical methods are most often used, with low-temperature treatment being the most common.

A significant number of methods have been developed and are currently used for the decontamination of meat and meat products. However, these methods possess several drawbacks, including alterations to organoleptic characteristics, complex application techniques, and insufficient scientific justification, which hinder their widespread adoption in production. Consequently, while numerous antimicrobial agents designed to reduce contamination of animal carcasses after slaughter have demonstrated their effectiveness, they also have drawbacks related to the deterioration of meat's appearance and potential toxicity to humans. This necessitates the search for safe and effective agents that can ensure the long-term storage of meat and meat products.

Conclusions

Both in the European Union and globally, there remains a traditional demand for safe and high-quality meat, which is an essential component of human nutrition. The safety and quality of meat depend significantly on the conditions of animal husbandry, feeding, and care. In addition to these factors, important roles are played by the conditions of animal preparation for slaughter, transportation, pre-slaughter holding, stunning, bleeding, evisceration, splitting carcasses into halves, post-slaughter cleaning, and cooling of the meat. A primary factor contributing to microbial contamination of carcasses during cooling and storage is the unsatisfactory state of the relevant facilities, as well as violations of the technological regimes for refrigeration treatment, which create favourable conditions for the growth and multiplication of microorganisms. A provisional classification of the main modern methods of meat processing aimed at reducing microbial contamination and extending its shelf life has been presented. These methods include physical techniques, the use of various chemical substances, biological technologies, and combined processing methods. Each technology has its own advantages and disadvantages. When selecting the optimal method to reduce bacterial contamination and prolong shelf life, it is essential to consider the chemical composition of the meat, the species of animal, the technological capabilities of the processing facility, the season, and other factors. The current approach, which takes into account the modern ecological state and the growing trend towards consuming organic products, underscores the importance of focusing on safe methods (without the use of toxic chemicals) and substances of natural origin for meat processing, aimed at improving quality and extending shelf life. It is known that most meat processing enterprises utilise organic acids to treat the surface of carcasses to reduce microbial contamination. However, these acids have several drawbacks, particularly their impact on organoleptic properties, necessitating the development of new methods for prolonging the shelf life of meat in a cooled state. Such methods may include the application of microbiological preparations, specifically special strains of lactic acid bacteria, which exhibit selective fermentation towards mono- and polysaccharides, do not adversely affect the organoleptic properties of meat, and display antagonism towards conditionally pathogenic and pathogenic microorganisms. Therefore, considering the research findings on the use of lactic acid bacteria and bacteriocins, and their detrimental effects on key pathogenic microorganisms for humans, including *E. coli, Salmonella* spp., and *Listeria monocytogenes*, it is essential to combine classical physical processing methods – such as temperature control, pressure application, and mechanical cleaning – with biological technologies to produce safe and high-quality raw meat. Thus, the utilisation of suspensions of lactic acid bacteria starters for the final treatment during the cooling of pork carcasses (or half-carcasses) in refrigeration chambers requires a detailed investigation into their impact on the quality and safety of pork, taking into account sensory properties and the overall appearance of the meat.

In the future, it is planned to investigate the effectiveness of using starter cultures of strains SafePro® B-SF-43 (*Leuconostoc carnosum*) and SafePro® B-2 (*Lactobacillus sakei*) as a final treatment for pork half-carcasses to achieve biopreservation and maintain freshness.

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None.

Conflict of Interest

None.

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Сучасні методи обробки сирого м'яса для зменшення мікробної контамінації

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Анотація. Існують різні методи збереження якості та подовження терміну придатності харчових продуктів. Сире м'ясо різних видів тварин – продукт, що піддається швидкому псуванню. Актуальність дослідження зумовлена необхідністю узагальнення сучасних знань стосовно підходів і методів подовження термінів зберігання безпечного та якісного м'яса та їх наукового обґрунтування. Дана робота була сфокусована на пошуку засобів, які знижують бактеріальне забруднення, оскільки саме мікроорганізми є головною причиною псування м'яса. Метою роботи був пошук найбільш перспективних та оптимальних методів для подовження термінів зберігання свіжості сирого м'яса. Для аналізу використовували інформацію наукових першоджерел, електронні ресурси, вивчали результати експериментальних даних щодо застосування науково обґрунтованих безпечних підходів. Здійснено огляд основних методів та заходів, які спрямовані на подовження термінів зберігання сирого м'яса. Встановлено переваги та недоліки різних методів обробки сирого м'яса, що діють бактерицидно чи бактеріостатично на різні, зокрема, патогенні мікроорганізми, які викликають не лише псування м'яса, але й можуть бути небезпечними факторами для потенційного споживача. Нині використовують традиційні, різноманітні нові та інноваційні методи. З урахуванням сучасних досягнень науки та технологій найперспективнішим є використання комплексних методів обробки сирого м'яса. Проаналізувавши результати досліджень багатьох науковців зроблено висновок, що найоптимальнішими є біологічні технології з використанням молочнокислих бактерій у поєднанні з традиційними методами фізичної обробки, а саме, охолодженням. Даний підхід зберігає свіжість м'яса та виявляє мінімальний вплив на органолептичні показники за дотримання температурних режимів та технології обробки культурами молочнокислих мікроорганізмів сирого м'яса. Прикладне значення цієї роботи полягає у встановленні найперспективніших напрямків для подальшого дослідження та вдосконалення наявних безпечних протимікробних препаратів, зокрема, використання різних штамів молочнокислих заквасок. Їх практичне застосування дасть можливість зберегти свіжість м'яса та подовжити його термін зберігання

Ключові слова: продукти забою; молочнокислі бактерії; знезараження протимікробними добавками; контроль якості і безпечності; протимікробні хімічні речовини