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Development of technology for extended-shelf-life meat products

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Abstract. The development of new technologies to preserve the quality of meat products is of significant relevance in light of the growing global demand for safe, durable, and functional food products that meet modern healthy eating standards. This is particularly important given the challenges associated with ensuring global food security. This study aimed to design an innovative production technology for meat products that ensures an extended shelf life without

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compromising their organoleptic properties. The research employed contemporary methods of physicochemical and microbiological analysis, along with biotechnological approaches, particularly the use of starter cultures of lactic acid bacteria and bifidobacteria. The findings confirmed the positive influence of probiotic cultures on the biochemical processes occurring in meat raw materials. Specifically, these cultures facilitated fermentation, maturation, and the development of stable organoleptic characteristics. Furthermore, it was established that the use of probiotics reduced water activity and pH levels, thereby significantly enhancing the microbiological stability of meat products. The analysis of technological parameters, such as salting, maturation, and drying periods, demonstrated their critical role in shaping the flavour and aroma profiles, texture, and colour of the final product. As a result of this study, innovative production technology for meat products was developed, enabling the creation of items with high protein content, low fat content, and stable microbiological safety, with an extended shelf life of up to 45 days. The practical value of this research lies in the potential for wide-scale implementation of the developed innovative technology in the food industry for the production of high-quality dry-cured and fermented meat products. These products meet contemporary standards of safety and nutritional value. The use of probiotic cultures contributes to the creation of products with enhanced organoleptic properties and additional functional benefits, aligning with healthy eating trends and addressing consumer demand for natural and environmentally friendly products

Keywords: biotechnology; dry-cured meat products; safety; expiration date; quality

Introduction

The most pressing global challenges (energy, environment, food) are particularly relevant to the food industry, and their solutions require fundamentally new approaches to raw material processing. The development and implementation of highly efficient equipment and technologies, as well as the creation of new-generation products, are priorities for the food industry. The current state and growth of specialised enterprises in Ukraine necessitate the optimisation of relationships between farms and the agro-industrial processing sector, as well as the improvement of the pricing mechanism for the formation of raw material and finished product markets. The rapid growth of the global population has led to food shortages, stimulating the development of technologies for growing agricultural products and raising livestock, and consequently, the production of food (Cherednichenko & Bal-Prylypko, 2019).

According to K. Pushparaj *et al.* (2024), cured meat products have a low tendency to lose fat during processing, which positively affects their appearance and visual appeal. A significant advantage of such products is their high storage stability due to the reduced rate of oxidation of bound fats, preventing rancidity. Their flavour profile is distinctive and intense, characteristic of mature meat products. An additional benefit of cured meat, used in the production of dry-cured meat products, is the preservation of all the nutritional and beneficial properties inherent in fresh meat. Moreover, a long shelf life (approximately 6 months) increases the convenience of its use. Such products become an optimal food option in conditions of limited access to traditional food, particularly during business trips, travel, or at work, providing a complete and nutritious diet.

O. Cherednichenko *et al.* (2021) noted a growing interest in organic food and healthy lifestyles in Ukraine. The development of functional food product formulations should be based on modern principles of balanced and nutritious diets. In this context, the production of dry-cured meat products holds significant potential, as this product category meets the requirements of healthy eating, characterised by high protein content and low fat levels. Moreover, due to specific processing technologies, such products contain virtually no flavour enhancers, trans fats, colourants, flavourings, or other harmful chemical components, further enhancing their nutritional value and safety.

J. Wang *et al*. (2020) assert that starter cultures play a pivotal role in the production of drycured and fermented sausages, providing controlled fermentation to achieve the desired texture, flavour, and colour of the final product. They also reduce the risk of undesirable microbial growth during ripening and storage. Globally, the primary criterion for selecting microorganisms for starter cultures is their impact on the sensory characteristics of the product under conditions of intensified and modernised production processes. The use of such cultures is crucial for ensuring the high quality and safety of meat products. B. Łaszkiewicz *et al*. (2021) described a series of experiments on colour stabilisation of meat products using sodium nitrite (E250). This substance plays a significant role in the formation of colour, flavour, and aroma, and partially influences microbial stability during storage. However, sodium nitrite is a toxic compound, and excessive consumption can lead to serious adverse health effects. For instance, the pharmacological toxic dose of sodium nitrite is 0.3 g. Even small amounts of free nitrite can cause the formation of methaemoglobin in the blood, leading to anaemia and serving as a precursor for carcinogenic nitrosamines. This highlights the need for strict control over the use of nitrites in the food industry to minimise risks to consumer health.

M. Shakil *et al*. (2022) investigated the challenges of reducing sodium nitrite content in meat product technology, highlighting its significance for public health. The current lack of full substitutes for sodium nitrite complicates its complete removal from formulations, necessitating the search for alternatives that can provide similar functionality while reducing the concentration of this compound in the final product. One promising solution is the use of beetroot extract (BE) in combination with denitrifying bacteria. Beetroot, due to its rich chemical composition, contains natural bioactive substances that not only bind and eliminate toxic compounds but also contribute to stimulating the body's immune system (Jha & Sit, 2022). This approach allows for the simultaneous preservation of product quality, reduced health risks for consumers, and increased functional value.

Therefore, the integration of plant-based additives into meat product manufacturing, combined with modern biotechnological methods, can serve as an effective alternative to chemically synthesised components. This paves the way for the creation of a new generation of products that meet modern requirements for safety, taste, and nutritional value. The development of such approaches requires further technological advancements and the implementation of innovative solutions in industrial practice. This research aimed to provide a scientific rationale and develop a comprehensive technology for producing meat products using probiotic cultures, ensuring their microbiological stability, extended shelf life, and high sensory quality, following modern food safety and functionality requirements.

Literature Review

Starter cultures have gained significant attention in the production of meat products. They are used in traditional products worldwide, including Turkey, Croatia, Romania, Greece, Italy, Spain, Portugal, Thailand, and China (Väkeväinen *et al*., 2020; Munekata *et al*., 2023; Liu *et al*., 2023). The application of these cultures is a crucial and sustainable method for preserving certain foods, offering recognised technological advantages. According to research by Y. Liu *et al*. (2023), various types and strains of microorganisms are used as starter cultures to inhibit the growth of pathogenic microorganisms and suppress the development of spoilage organisms. Depending on technological requirements and consumer preferences, different strains are used in various products. According to M. Fuka *et al.* (2020), the most widely used starter cultures in meat products are LAB (Gram-positive, catalase-negative cocci or bacilli), Gram-positive, catalase-positive cocci, mainly CNS, and *Micrococcaceae*, moulds, or yeasts, whose metabolism produces several compounds with antimicrobial activity. These microbial cultures can be used as individual or mixed cultures.

According to S. Smaoui *et al.* (2024), LAB used as starter cultures in fermented meat products are typically facultative anaerobes and primarily belong to the genera *Lactobacillus, Leuconostoc, Pediococcus, Lactococcus,* and *Enterococcus*. Among CNS species most frequently used for meat fermentation, facultative anaerobes *Staphylococcus carnosus* and *S. xylosus* are commonly employed (Stavropoulou *et al.*, 2018). In the *Micrococcaceae* family, *Kocuria spp.*, which are aerobes, are primarily used for sausage fermentation (Ding *et al.*, 2021). Research by M. Fuka *et al.* (2020) has shown that the most common yeasts used as meat starter cultures are *Debaryomyces spp*. and *Candida spp.*, which can exhibit aerobic or facultatively anaerobic metabolism. Both bacterial and yeast starter cultures were inoculated into the meat batter by researchers.

Mould starters, being strict aerobes, are inoculated on the surface and primarily belong to the species *Penicillium nalgiovense* and *P. gladioli* (Fuka *et al.*, 2020). Reuterin (3hydroxypropionaldehyde) is a well-known broad-spectrum antimicrobial compound produced by *Lactobacillus reuteri* during anaerobic fermentation (Mu *et al.*, 2018). According to S. Soltani *et al.* (2021), reuterin can be converted into various compounds, making it challenging to pinpoint the exact mechanism behind its antimicrobial activity. Reuterin spontaneously converts to acrolein, a cytotoxic electrophile, but it is reuterin, not acrolein, that is responsible for the antimicrobial effect. S. Bennett *et al.* (2021) and H. Yehia *et al.* (2022) investigated the potential use of reuterin as a food additive to prevent food spoilage and the growth of pathogens in various food matrices. Reuterin also demonstrated its effectiveness in reducing viable cells of *E. coli* O157:H7 and *L. monocytogenes* in pork over a storage period of 1 week.

Finally, it has been demonstrated that certain LAB possess a nitrite reductase enzyme system, which under anaerobic conditions reduces nitrite, a preservative used in some meat products, suggesting that LAB contribute to nitrite depletion in many foods (Liu *et al.*, 2023). This is a significant finding for food safety, considering the EFSA recommendations to reduce the use of nitrates and nitrites in food preservation. The presence of nitrite reductase and heme-dependent nitrite reductase, capable of converting nitrite to NO, NO_2, and N_2O, has also been described in *Lb. sakei* (Liu *et al.*, 2023). In fact, nitrite concentrations were significantly lower in fermented sausages inoculated with *Lb. sakei* compared to control sausages, likely due to its nitrite reductase, which is responsible for nitrite depletion. In the scientific manuscript by M. Daneshniya *et al.* (2023), it is established that several factors have a significant impact on combating *L. monocytogenes* and *C. botulinum*, and require low concentrations of enzymes for rapid nitrite metabolism. Therefore, developing technology for long-shelf-life meat products, such as cured meats, using bacterial preparations and reducing sodium nitrite content is relevant for food safety.

Materials and Methods

Experimental research was conducted in the laboratories of the Department of Technologies of Meat, Fish and Marine Products at the National University of Life and Environmental Sciences of Ukraine (NULES) and the Institute of Food Resources of the National Academy of Agrarian

Sciences of Ukraine (NAAS) during the period from 2019 to 2022. The developed technology was tested under the conditions of the production and research laboratory of NULES Ukraine.

The development of dry-cured meat product technology involved three main stages. The first stage focused on investigating the impact of starter cultures on biochemical processes in meat raw materials during salting, as well as justifying the use of beetroot extract (BE) as a substitute for reducing the sodium nitrite content in the formulation of extended-shelf-life meat products. The second stage examined the quality and safety indicators of the meat raw materials, including the structural-mechanical and physicochemical properties of beef used for experimental samples. The third stage involved the industrial testing of the developed biotechnology. Comprehensive quality and safety indicators of the final products were assessed, including physicochemical, microbiological, and organoleptic parameters.

Standard analytical methods were employed to ensure the accuracy and objectivity of the research. Moisture content was determined by drying the sample to constant mass at a temperature of 103 ± 2°C (DSTU ISO 1442:2005). The protein content was measured using the Kjeldahl method (DSTU ISO 5983:2003), fat content was determined with a Soxhlet extraction apparatus (DSTU ISO 1443:2005), and table salt content was assessed using the Mohr method (DSTU ISO 9297:2007). The energy value of the product was calculated according to DSTU 4590:2006. Active acidity (pH) was measured following DSTU ISO 2917:2001.

The oxidation-reduction potential (ORP) was measured using the multifunctional "Combo" device. Water activity (a_w) was assessed using the *HygroPalm* HP23-AW device (UK) based on the "dew point" principle (DSTU ISO 21807:2007). Sensory evaluation was conducted according to DSTU 4823.2:2007. Water-holding capacity (WHC) and meat plasticity were determined using the Grau and Hamm method modified by Volovinska (DSTU ISO 1442:2005). The ultimate shear stress was measured using an *Ulab* 3-31 penetrometer. Drying loss histograms were calculated using *Multitab* software. The yield of the final product was determined by weighing the item on analytical scales with a precision of 0.001 g, both before and after thermal processing. This approach allowed for the assessment of weight changes during production (Mushtruk *et al.*, 2023).

The quantitative evaluation of colour characteristics was conducted using the RGB system (Standard Practice for Calculating Yellowness and Whiteness Indices from Instrumentally Measured Colour Coordinates: E 313-20, 2020) and a multifunctional *Epson Stylus* TX400 device. Colour codes were identified with the *Adobe Photoshop CS6* software package. The obtained RGB colour coordinates were used to calculate L°, a°, and b° coordinates (colour intensity, redness, and colour saturation) within the international CIE colourimetric system. Based on these values, the colour hue (H (*Redness index*)) and chroma (C (the level of colour of the sample relative to the brightness of an absolutely white object)) were calculated to determine the redness index and the sample's colour saturation relative to the brightness of a purely white object (Standard Practice for Calculating Yellowness and Whiteness Indices from Instrumentally Measured Colour Coordinates: E 313-20, 2020) using the following formulas (1), (2):

$$H = \frac{a}{b}, \quad (1)$$

$$C = a^2 + b^2, \quad (2)$$

where a is the redness coordinate, b is the colour saturation coordinate.

Microbiological safety indicators were determined following the DSTU EN ISO 15189:2015 methodology. The formulations of the experimental samples incorporated sea salt, which possesses unique properties due to its enrichment with macro- and microelements of oceanic origin. Compared to rock salt, sea salt contains less sodium chloride, offers a milder flavour, and includes approximately 80 additional components such as calcium, magnesium, potassium, iodine, and other elements.

One of the objectives of the study was to eliminate sodium nitrite from the formulation of extended-shelf-life meat products. To achieve this, beetroot extract (BE) was employed as an organic substitute for sodium nitrite, in combination with denitrifying microorganisms and a starter culture. To develop the desired product properties and establish an effective barrier against pathogenic microflora during salting, the preparation B-LC-78, containing *Pediococcus acidilactici* and *Staphylococcus carnosus*, was utilised. Optimal conditions for their growth included oxygen availability, a minimum temperature of +6°C, and a limited salt concentration (up to 10% in water).

The salting process was conducted using a dry method at a temperature of 4-6°C with unrestricted oxygen access. To assess the effectiveness of this approach, three samples were developed and studied: control sample – beef sticks without the addition of starter cultures to the salting mixture; experimental sample 1 – beef sticks with the addition of the starter cultures B-LC-78 and CS-300, along with sea salt; experimental sample 2 – beef sticks with the addition of the starter cultures B-LC-78, CS-300, sea salt, and beetroot extract.

Results and Discussion

The detailed composition of the curing mixtures for each sample is presented in Table 1. This allowed for a comparison of the classical and experimental production technologies, assessing their impact on product quality and safety.

Table 1. *Composition of the curing mixture for the control sample per 100 kg of raw material*

Ingredients	Amount, kg
for the control sample	
NaCl *(sodium chloride)*	3.5
E 250 *(sodium nitrite)*	0.015
Glucose *(dextrose)*	1
Spices	1.2
Sodium isoascorbate (E 316)	0.07
for experimental sample No. 1	
Sea salt	3.3
Sodium nitrite (E 250)	0.015
Glucose (*dextrose*)	1
Spices	1.2
Sodium isoascorbate (E 316)	0.07
Preparation B-LC-78 (*bacterial*)	0.025
Preparation CS 300 (*bacterial*)	0.025
Sea salt	3.3
for experimental sample No. 2	
Sea sodium salt	3.3
Beetroot extract	2
Glucose (*dextrose*)	1
Spices	1.2
Sodium isoascorbate (E 316)	0.07
Preparation B-LC-78 (*bacterial*)	0.025
Preparation CS 300 (*bacterial*)	0.025

Source: authors' development

Lactic acid bacteria, which are a component of the typical microflora of meat raw materials, are mostly capable of developing during salting. Therefore, in this study, the amount of "extraneous" lactic acid microflora in the control samples was also determined.

The results of the experiment (Fig. 1) demonstrated a rapid growth of the viable cell population in the experimental samples.

Thus, in experimental sample No. 1, the number of viable lactic acid bacteria (LAB) increased from 6.11 to 7.02 log CFU/g within 24 hours. In a similar sample No. 2, an increase from 6.09 to 7.01 log CFU/g was observed. The control sample showed a slower growth rate of the microflora – from 2.03 to 2.9 log CFU/g. These results are consistent with previous studies, which confirm the accelerated growth of beneficial microflora under conditions of adding starter cultures, changing the level of acidity and redox potential (ORP). Together, these factors help assess the stability of *Pediococcus acidilactici* under the conditions of the raw cured product manufacturing process and support its potential use for fermenting meat raw materials.

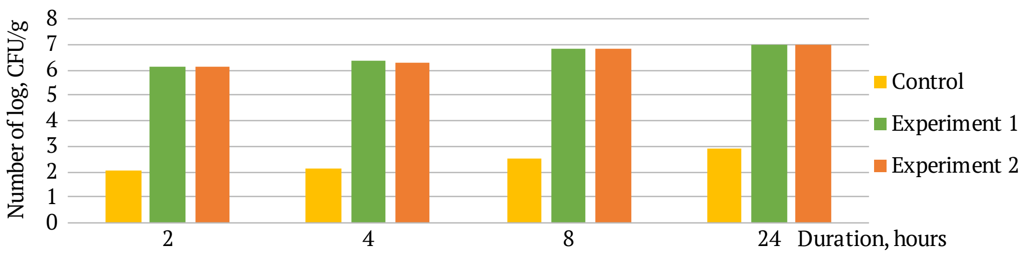

Figure 1. Dynamics of the number of lactobacilli in control and experimental meat samples during salting

Source: authors' development

Analysis of the dynamics of changes in pH and redox potential (ORP) of meat samples (Fig. 2) indicated the influence of the activity of the microflora that was introduced into the raw material. The vital activity of this microflora contributes to the fermentation process of dextrose (added to the curing mixture) and meat carbohydrates, which causes the formation of organic acids and, as a result, a decrease in the pH of the medium. In the control samples, a tendency towards a decrease in pH was also observed, but this process developed more slowly than in the experimental samples.

In the experimental samples, the pH decreased from 5.67 to 5.53 within 24 hours, which is a result of the enzymatic activity of lactic acid bacteria, which process dextrose and carbohydrates, forming organic acids (including lactic acid), thus lowering the pH level. It is known that at this stage, when the pH of the meat reaches the range of 5.5-5.7, tenderisation of muscle fibres, partial denaturation of proteins, and the formation of flavour compounds occur, affecting the organoleptic characteristics of the product. The decrease in ORP in the experimental samples is explained by the production of antioxidants by microorganisms. As shown in Figure 2, the ORP in the control samples increases from 150 to 239 mV after 24 hours of incubation, which may be due to oxidative processes and the development of indicator microflora.

The salting process, along with the redistribution of salt components, also causes changes in the moisture content of meat, accompanied by changes in WHC. These changes are of significant technological importance as they affect the product yield and its quality, including juiciness, texture, colour, taste, and aroma. The

WHC of meat products was investigated to assess the ability of the meat raw material to bind and retain moisture during processing and to ensure the yield of the finished product. The dynamics of WHC changes were studied after the introduction of the curing mixture with starter cultures into the meat raw material over the first 24 hours (Fig. 3).

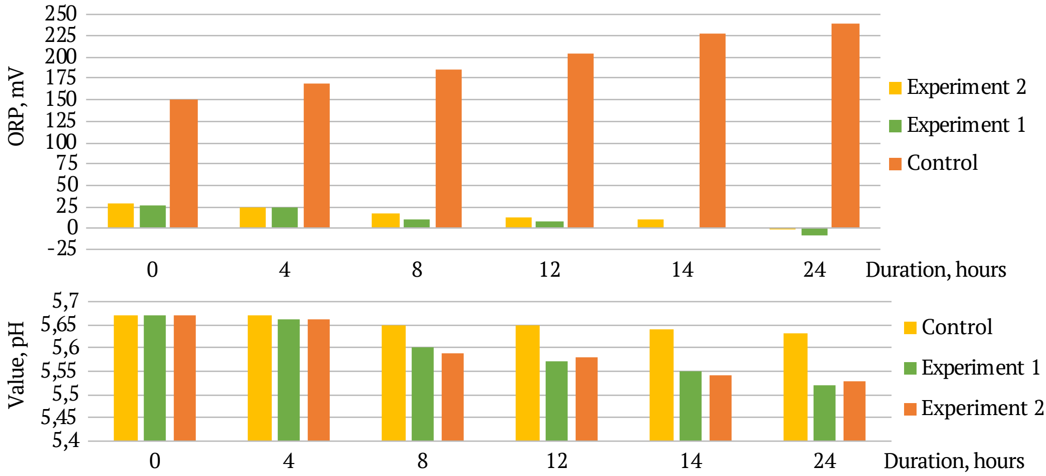

Figure 2. Variation in the oximetric (ORP) and pH values of control and experimental meat samples throughout the salting process

Source: authors' development

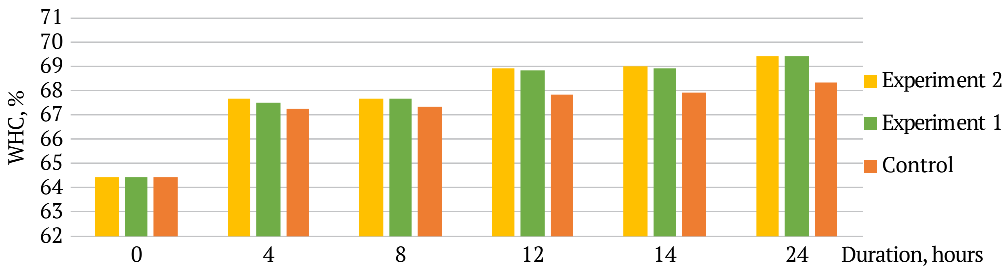

Figure 3. Dynamics of the change in water-holding capacity

Source: authors' development

During the salting of meat, an increase in WHC was observed in all samples. This is due to the fact that sodium chloride promotes the formation of a tissue fluid concentration that is close to the optimum for the solubility of the actomyosin fraction of proteins. As a result, the number of hydrophilic centres of myofibrillar proteins increases, which in turn leads to an increase in the amount of adsorption-bound water and an increase in the WHC of meat. It should be noted that the level of WHC is also influenced by factors such as the pH and redox potential of the meat system. The vital activity of *Pediococcus acidilactici* and *Staphylococcus carnosus* leads to the formation of organic compounds that affect meat proteins, in particular through a decrease in pH. As shown in Figure 3, the experimental samples, in which a bacterial preparation was used during salting, are characterised by a higher WHC value compared to the control sample. In experimental sample No. 1, the

WHC increased from 64.41% to 69.42% within 24 hours, while in the control sample, a slower increase in this indicator was observed – from 64.41% to 68.32%.

Reducing water activity in food products is an effective method of preventing microbial spoilage and several chemical reactions that can degrade product quality during storage. To investigate the effect of a bacterial preparation on the amount of water activity in meat raw materials, changes in water activity and moisture content dynamics in meat were studied over 24 hours from the beginning of salting. The results of this study are presented in Figure 4.

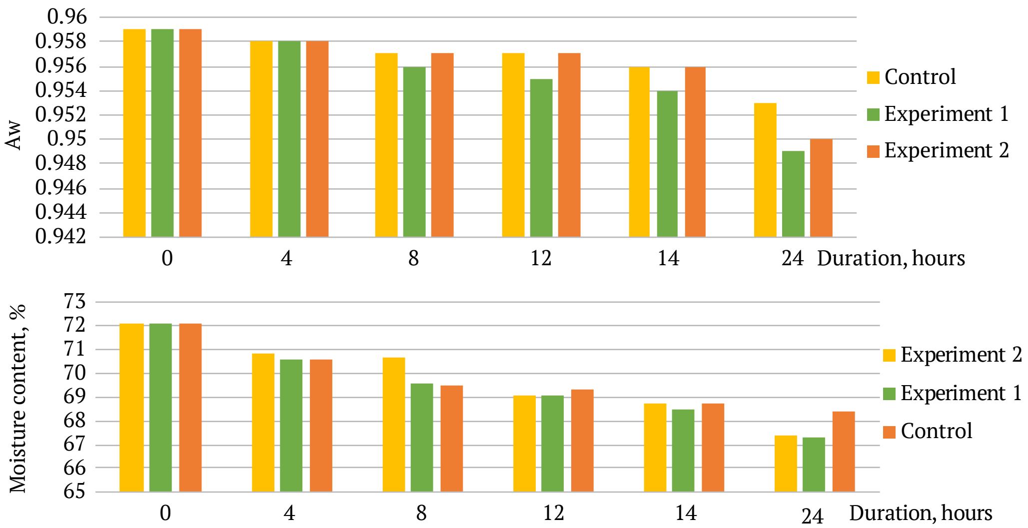

Figure 4. Change in moisture content and water activity (Aw) during the salting process
Source: authors' development

In traditional salting methods, regardless of the brine concentration, including dry salting, at the initial stage, the osmotic pressure of the brine is significantly higher than the osmotic pressure of the tissue fluid of the meat. This causes tissue dehydration. However, as salts and products of the breakdown of meat components accumulate by diffusion, the osmotic pressure in the meat increases, while in the brine it decreases. Such dynamics of processes lead to an increase in the water-holding capacity of meat and a transition from the dehydration phase to the hydration phase (Mushtruk *et al*., 2023).

Meat texture is a crucial parameter for assessing product quality and determining the duration of processing. It reflects structural-mechanical characteristics such as plasticity, elasticity, and strength. Research has shown that the presence of organic acids during salting enhances proteolysis, positively affecting the meat's plasticity (Sun *et al*., 2022). The influence of acidic compounds also leads to the swelling of collagen bundles and the weakening of intermolecular cross-links, resulting in a softer and more tender texture. The change in meat plasticity during salting is depicted in Figure 5.

According to the obtained data (Fig. 5), the plasticity of the samples increases proportionally with ripening time in both experimental and control samples, which is due to changes in the colloidal-chemical state of proteins and the activation of tissue enzymes during salting. The highest plasticity was observed in the experimental samples, reaching a value of 2.95×10^{-4} m^2 after 24 hours of salting. For the control sample, this value was 2.69×10^{-4} m^2 after the same period. These changes can be explained by biochemical processes, in particular the proteolytic activity of lactic acid bacteria and the accumulation of their metabolites, which contribute to changes in the surface tension of the meat raw material and affect soluble meat proteins.

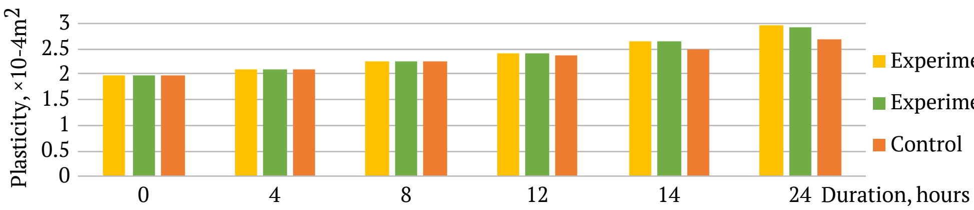

Figure 5. Alterations in the plasticity of meat raw materials during the salting process
Source: authors' development

The ultimate shear stress in both experimental and control samples exhibited a decreasing trend. Throughout the salting process, the values for the experimental samples remained lower than those of the control samples. The dynamics of changes in ultimate shear stress during meat salting are depicted in Figure 6. After 24 hours, the experimental samples reached an ultimate shear stress of 161 kPa, while the control samples had a value of 177 kPa. This confirms that the proteolytic activity of bacteria and the accumulation of their metabolites affect the soluble proteins in the meat and alter the surface tension of the meat raw material.

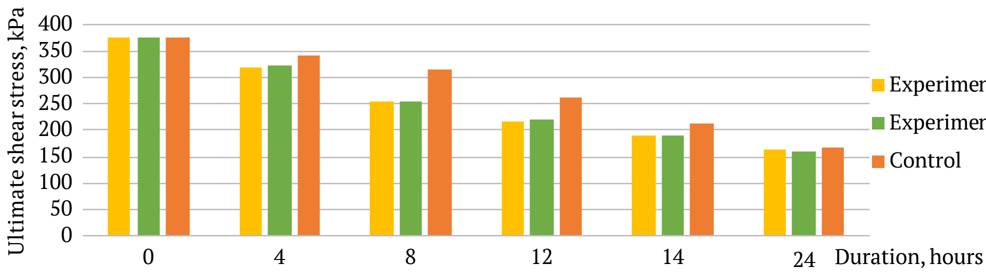

Figure 6. Change in ultimate shear stress of meat raw materials during the salting process
Source: authors' development

The results of the conducted research confirm the positive impact of adding bacterial preparations to meat raw materials during salting. This allows for improving the structural and mechanical properties of the product, reducing losses during heat treatment, and increasing water-holding capacity, which collectively positively affects the quality of the finished product and contributes to increasing the microbiological stability of the process. M. Shakil *et al*. (2022) stated, that sodium nitrite, due to its versatility and effectiveness, is indispensable in the meat industry, but its use is associated with certain risks, as it can be a precursor to carcinogenic nitrosamines. Given these risks, modern meat processing technologies involve the use of beetroot extract (BE) together with denitrifying bacteria to reduce the nitrite content in the product and also to improve colour formation.

Beetroot contains betaine and betanin, which have healing properties. It is known that these compounds contribute to strengthening blood vessel walls, and are effective means of preventing colds, overloads of the body and immunodeficiency states, in particular in connection with carcinogenesis and the effects of radiation. Betanin and betaine also belong to lipotropic substances that are involved in fat metabolism, due to their chemical similarity to choline and lecithin (Zheplinska *et al.*, 2020). Nitrates, which are naturally found in beetroot, can only be reduced to nitrites by a microbiological pathway, thanks to the actions of nitrate-reducing bacteria. Thus, the use of vegetable extracts can be a key step in preserving the high-quality characteristics of the product, ensuring its safety for the consumer.

The starter culture Bactoferm CS-300, containing *Staphylococcus carnosus* bacteria capable of nitrate reduction, and SafePro B-LC-78, which includes both *Staphylococcus carnosus* and *Pediococcus acidilactici*, actively influence the nitrate reduction process. The efficiency of this reaction depends on the pH of the environment, with reduction reactions occurring more intensely at lower pH values (Guimarães *et al.*, 2022). The optimal pH range for colour formation is between 5.0 and 6.0. Studies have shown that the addition of starter cultures containing lactic acid bacteria significantly accelerates the decrease in pH. For a more accurate determination of the colour characteristics of the samples, a sensory analysis was conducted, supplemented by additional studies, the results of which are presented in Table 2.

Table 2. *Colour characteristics of control and experimental samples of long-term stored beef products (n = 3, p ⩾ 0.95)*

Indicator	Studied samples		
	Beef		
	Control sample	**Experiment 1**	**Experiment 2**
**L* Colour Intensity	157.22 ± 0.540	157.19 ± 0.424	157.23 ± 0.375
**a* Redness	8.5 ± 0.22	8.4 ± 0.25	8.4 ± 0.64
Redness index (H)	0.868 ± 0.342	0.877 ± 0.541	0.876 ± 0.223
**C* Colour Level relative to Brightness of Absolute White Object	169 ± 0.45	171 ± 0.38	172 ± 0.11

Source: authors' development

Analysing the data presented in Table 4, it can be concluded that the use of starter cultures in combination with beetroot extract (BE) during the colour formation of long-term stored meat products has a positive impact on their colour characteristics. Using beef products as an example, it can be seen that experimental sample No. 2, treated with BE, has colour indicators that are not inferior to either the control sample or experimental sample No. 1, where sodium nitrite was used. This confirms the assumption that beetroot contains enough nitrates to ensure the colour formation process of the meat product.

In addition, experimental sample No. 2 demonstrates the best results in terms of colour intensity, redness index, and chroma, indicating the high efficiency of using BE. This proves that reducing the level of residual sodium nitrite in the product contributes to a more active formation of nitrosopigments, which in turn improves the colour indicators of the finished meat product. Starter cultures are an important tool for ensuring the safety of fermented meat products, as they contribute to reducing the growth of microorganisms that can cause spoilage or be pathogenic. This process occurs through the production of metabolites or the competitive exclusion of other microbes. Thanks to starter cultures, the need to use chemical additives such as nitrites and nitrates is reduced. Moreover, starter cultures are able to metabolise these compounds, which reduces their residual content in finished products.

Starter cultures not only positively impact product safety but also improve batch-to-batch consistency, reduce production time, and enhance sensory properties. Due to these effects, starter cultures play a multifunctional role in the technology of fermented meat product production. Experimental studies have shown that the addition of the bacterial preparation B-LC-78 and the additive CS-300 in combination with beetroot extract (BE) to the curing mixture significantly improves the structural-mechanical, physicochemical, and sensory characteristics of the finished meat product. This has allowed for the improvement of the technology for producing long-term stored dry-cured meat products, increasing their biological and nutritional value.

The improved technology involves the additional introduction of a mixture of bacterial preparations B-LC-78 and CS-300, as well as BE, in doses that meet the requirements of the technological process. This allows for a reduction in production time, improvement of the product's sensory properties, and an increase in its shelf life. As a result of the experiment, dry-cured products were produced using the improved technology, applying a technological scheme that was implemented in the research laboratory of the National University of Life and Environmental Sciences of Ukraine. The improved technological scheme for the production of dried meat products with an extended shelf life is presented in Figure 7.

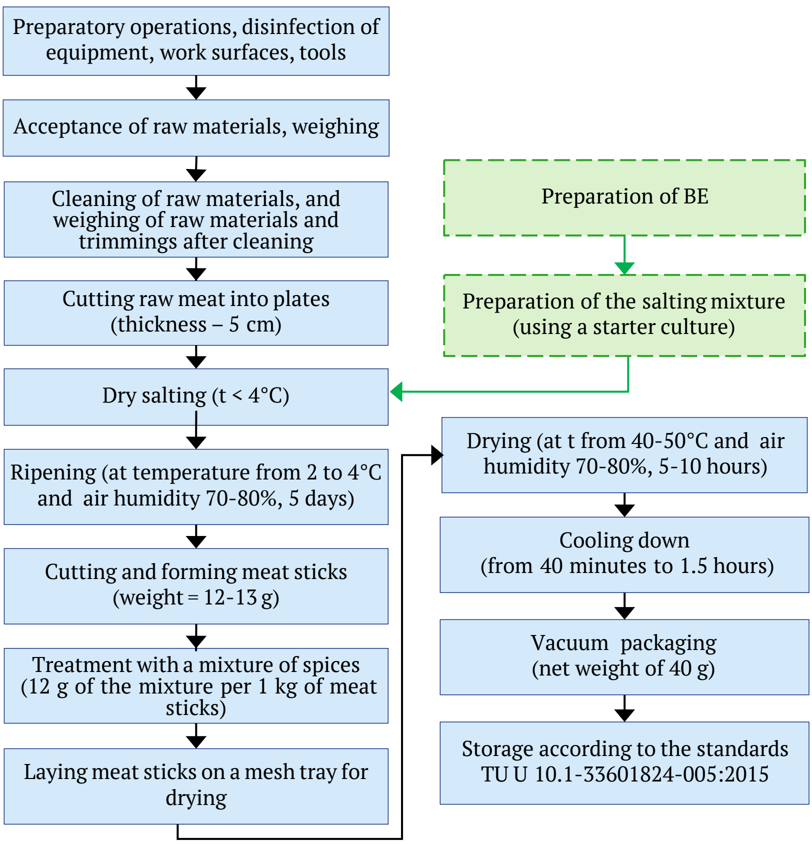

Figure 7. An improved technological scheme for the production of cured meat products with an extended shelf life

Source: authors' development

The production process involved preparing the meat (receiving, weighing, cleaning), mincing, salting, ripening, and drying. High-quality beef (longissimus dorsi muscle) was used and sliced into 5 cm thick plates. The meat was dry-salted using specialised curing mixtures. After salting, the raw material was aged for 3-4 days at a temperature of 2-4°C, after which the plates were cut into sticks (12-13 g) and treated with spices. Drying was carried out at a temperature of 40-50°C for 5-10 hours, depending on the type of raw material. After drying, the product was cooled, which took from 40 minutes to 1.5 hours depending on the microclimate in the production area. An innovation in the technology development was the introduction of bacterial preparations B-LC-78 and CS-300 directly into the curing mixture, which contributed not only to improving the quality of the product but also to maintaining its safety and increasing its shelf life.

The advanced biotechnology employed for producing extended-shelf-life meat products has resulted in a product of superior quality, particularly in terms of nutritional value, microbiological stability, and safety. The substitution of sodium nitrite with extracts from biotechnological starter cultures has significantly reduced the use of chemical preservatives while preserving all organoleptic characteristics. The introduction of the bacterial preparations B-LC-78 and CS-300, along with beetroot extract, has not only enhanced the final product's quality but also ensured adequate microbiological stability. The use of sea salt, another component of the technological scheme, has contributed not only to preservation but also to increasing the product's nutritional value. Compared to traditional technologies that relied on nitrites and nitrates, these innovations have achieved a reduction in residual chemical compounds, positively impacting product safety.

The implementation of new technologies in production laboratories is particularly significant, allowing for controlled conditions of ripening, drying, and storage, as well as vacuum packaging, which ensures a long shelf life without compromising quality. Considering all these factors, it is possible to significantly improve the final quality indicators of the product and make it more appealing to consumers. These results support the feasibility of introducing bacterial cultures and environmentally friendly technologies into the production of extended-shelf-life meat products, aligning with contemporary demands for healthy eating and environmental safety. They also open up prospects for further research and expanding production capabilities in this field.

Conclusions

Through a study of the chemical composition, production technology, and bioprotective and colour-regulating properties of bacterial preparations, their significant impact on the physicochemical and microbiological characteristics of meat raw materials has been established. Specifically, the introduction of bacterial preparations at a rate of 25 g per 100 kg of raw material provided a complex effect, including increased water-holding capacity, plasticity of the raw material, and a rapid decrease in pH and redox potential (ORP). Experimental studies have shown that 24 hours after the introduction of the preparations, the concentration of viable lactic acid bacteria increased 2.4 times compared to the control. As a result of the activity of these bacteria, a decrease in the pH of the medium from 5.67 to 5.53 was observed, which is due to the fermentation of dextrose and carbohydrates with the formation of carboxylic acids, in particular lactic acid. This process is effective for controlling the pH of meat raw materials, which positively affects the stability of the product.

In experimental samples containing bacterial preparations, water-holding capacity increased by 1.01 times compared to control samples, while shear stress decreased 2.3 times after 24 hours. This indicates an improvement in the structural and mechanical properties of the meat, reduced cooking losses, and an enhancement in the quality of the final product. Additional data confirms the importance of using natural beetroot extract in combination with denitrifying bacteria as an effective alternative to sodium nitrite. This combination allows for the complete elimination of sodium nitrite in the production of dry-cured meat products while maintaining colour stability, which is critical for producing high-quality meat products. Thus, the results of the study highlight the significant potential of bacterial preparations for improving the quality of meat products, stabilising their colour characteristics, and reducing the use of chemical preservatives. These innovations contribute to the development of safe and efficient technology for producing extended-shelf-life meat products.

Future research in this area should focus on a detailed study of the impact of various types of probiotic bacteria on fermentation processes in meat raw materials, aiming to optimise technological parameters such as salting time, ripening, and drying. Further attention should be paid to the development of new compositions of natural extracts with increased antioxidant and bioprotective activity, which can provide additional protection against oxidation and microbial spoilage. A significant direction is the scaling up of proposed technologies for industrial use and the evaluation of their economic efficiency. It is also advisable to expand research to other types of meat products to verify the universality of the proposed approaches, as well as to study their impact on the organoleptic properties, safety, and functionality of the final products in the context of modern consumer demands.

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Conflict of Interest

The authors declare no conflict of interest in the publication of this article.

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Розроблення технології м'ясних продуктів подовженого терміну зберігання

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Анотація. Розроблення нових технологій для збереження якості м'ясних продуктів є надзвичайно актуальним у контексті зростаючого глобального попиту на безпечні, довговічні та функціональні харчові продукти, що відповідають сучасним стандартам здорового харчування, особливо з урахуванням викликів, пов'язаних із забезпеченням продовольчої безпеки у світі. Метою цього дослідження було створення інноваційної технології виробництва м'ясних продуктів, яка забезпечує їх подовжений термін зберігання без втрати органолептичних характеристик. У роботі застосовувалися сучасні методи фізико-хімічного та мікробіологічного аналізу, а також біотехнологічні підходи, зокрема використання стартових культур молочнокислих бактерій і біфідобактерій. Проведені дослідження підтвердили позитивний вплив пробіотичних культур на біохімічні процеси, які відбуваються у м'ясній сировині. Зокрема, вони сприяли ферментації, дозріванню та формуванню стійких органолептичних характеристик. Окрім цього, було встановлено, що використання пробіотиків дозволяє знизити активність води та рівень pH, що суттєво покращує мікробіологічну стабільність м'ясних продуктів. Аналіз впливу технологічних параметрів, таких як періоди засолу, дозрівання та сушки, показав, що вони мають ключове значення для формування смакових і ароматичних властивостей, текстури та кольору кінцевого продукту. У результаті роботи було розроблено інноваційну технологію виробництва м'ясних продуктів, яка дозволяє отримати вироби з високим вмістом білка, низьким вмістом жиру та стабільною мікробіологічною безпечністю, із подовженим терміном зберігання до 45 діб. Практична цінність проведеного дослідження полягає у можливості широкого впровадження розробленої інноваційної технології на підприємствах

харчової промисловості для виробництва високоякісних сирокопчених і сиров'ялених м'ясних виробів, які відповідають сучасним стандартам безпечності та корисності харчових продуктів. Використання пробіотичних культур сприятиме створенню продуктів із покращеними органолептичними властивостями та додатковими функціональними перевагами, що відповідають тенденціям здорового харчування та задовольняють попит споживачів на натуральні та екологічно чисті продукти

Ключові слова: біотехнологія; в'ялена м'ясна продукція; безпечність; термін придатності; якість