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THE USE OF STARTER CULTURES IN THE TECHNOLOGY FERMENTED MEAT PRODUCTS

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Agunova L. Candidate of Technical Sciences, docent
Department of meat, fish and seafood technology
Odesa National University of Technology
112 Kanatna Street, Odesa, Ukraine, 65039

Correspondence:

L. Agunova
E-mail: agunova.lora@gmail.com

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Abstract. This article summarizes scientific data on the biochemical mechanisms of action of starter cultures used in fermented meat product technology and examines their effect on product safety, shelf life, and nutritional and biological value. The use of starter cultures is a key approach to controlling fermentation, ensuring production reproducibility and the safety of finished products. The main groups of microorganisms – lactic acid bacteria, coagulase-negative staphylococci, yeasts, and moulds – play an important role in the development of sensory attributes, colour stabilization, aroma formation, and product texture. Microbiological safety is ensured by a rapid decrease in pH, competitive exclusion of undesirable microorganisms, and the production of organic acids and bacteriocins. Combined starter cultures comprising lactic acid bacteria and coagulase-negative staphylococci are recognized as the most effective. Starter cultures contribute to shelf-life extension through the application of hurdle technology, integrating biological preservation with modern packaging technologies. Microbial proteolysis and lipolysis contribute to stable sensory characteristics and promote the release of free amino acids and bioactive peptides, thereby enhancing protein digestibility. The use of probiotic strains capable of synthesising γ-aminobutyric acid and other biologically active compounds is considered promising. At the same time, several risks exist, including the dissemination of antimicrobial resistance, bacteriophage contamination, the formation of biogenic amines, and the presence of virulence factors, necessitating genomic screening prior to the application of new strains in meat product production. Promising research directions include the selection of indigenous strains, the development of multi-strain microbial cultures, the creation of functional meat products, and the introduction of sustainable packaging solutions. These directions represent a strategic pathway to improve competitiveness of the Ukrainian meat processing industry and ensure alignment with European quality and safety standards.

Keywords: starter cultures, fermented meat products, product safety, process reproducibility, shelf life, nutritional value

Introduction. Formulation of the problem

Meat from healthy animals is generally considered sterile during life, and the presence of microorganisms in raw meat and finished meat products results from endogenous and exogenous contamination from the gastrointestinal tract, skin surface, equipment, water, air, and workers' hands during slaughter, bleeding, evisceration, and carcass cutting [1]. The high nutrient content, high water activity (a_w), and slightly acidic pH provide a favourable environment for the growth of microorganisms after slaughter. In accordance with national legislation [2], the total viable count in high-quality meat after slaughter shall not exceed 1×10^5 CFU/cm². As a result, the microflora of fresh meat is a complex and dynamic system comprising various groups of microorganisms. These consist predominantly of 90 – 95% bacteria (*Pseudomonas*, *Brochothrix*), lactic acid bacteria (*Lactobacillus*, *Leuconostoc*, *Carnobacterium*), enterobacteria (*Escherichia*, *Enterobacter*, *Serratia*, *Proteus*, *Acinetobacter*, *Moraxella*, *Shewanella*, *Staphylococcus*, *Micrococcus*, *Clostridium*, *Aeromonas*, *Flavobacterium*, *Alcaligenes*, *Alteromonas*, *Enterococcus*, *Streptococcus*), yeasts (*Candida*, *Cryptococcus*, *Rhodotorula*), and moulds (fungi) (*Cladosporium*, *Sporotrichum*, *Geotrichum*, *Penicillium*, *Mucor*) [3]. The presence, abundance, and composition of microorganisms have a significant impact on meat quality and safety and determine its suitability for further processing. To maintain high quality of raw meat materials cooling, freezing, and packaging under modified atmosphere conditions, as well as treatment using vacuum packaging, high hydrostatic pressure, and ionising radiation, are

recommended [4, 5, 6]. However, in meat processing, the influence of microorganisms is more extensive and is not limited to undesirable changes. Through the action of microbial enzymes, a wide range of beneficial transformations occur in meat systems, leading to a reduction in pH, the development of aroma, flavour, colour, and texture, and the acceleration of meat maturation [7].

Foods that have undergone microbial fermentation have been part of the human diet since the Neolithic era. It is clear that in ancient times, and indeed up until the 19th century, fermentation took place under the influence of spontaneous natural microflora, and the first scientists to draw attention to the role of specific microorganisms were J. Lister, L. Pasteur and R. Koch [8, 9, 10].

The positive effects of specific microorganisms or microbial consortia on changes in meat and meat products have provided the basis for their application as starter cultures in production to ensure product safety, extend shelf life, and improve process stability and reproducibility, as well as to enhance organoleptic properties and nutritional value. These microorganisms subsequently became known as starter cultures or leaven.

In Ukraine, the use of microorganisms in food production is regulated by the Ukrainian Law "On the Basic Principles and Requirements for Food Safety and Quality" under general food legislation. However, there are currently no specific regulations governing the use of starter cultures. As an EU candidate country, Ukraine is harmonising its food legislation with European standards; accordingly, starter cultures are classified as food ingredients rather than food additives. Their use is governed by general food legislation provisions concerning safety, labelling, and the responsibilities of food business operators.

As reported by [11], food cultures are safe, live microorganisms, including bacteria, yeasts, and filamentous fungi (moulds), that are used in food production and are themselves food ingredients.

Food culture preparations are mixtures consisting of concentrates containing one or more viable strains of microorganisms of one or more species, at levels of $>10^8$ CFU/g or cm^3 for bacteria and yeasts and $>10^7$ CFU/g for filamentous fungi. They may also include metabolites, residual fermentation media components, and carrier substances such as carbohydrates, organic acids, minerals, and vitamins, which support microbial survival, stability, preservation, and technological application in food systems.

In the literature, food cultures are also referred to as starter cultures, milk cultures, yoghurt cultures, ripening cultures, meat cultures, and sausage cultures, probiotics, lactic acid bacteria, etc.

In the European Union, information regarding the use of microorganisms is coordinated by the European Federation of Food and Fermentation Cultures (EFFCA), which was founded in 1992. Its activities involve monitoring regulatory and scientific developments affecting microbial cultures, their production, and use; facilitating information exchange between members, the scientific community, and government bodies; and cooperating with a wide range of stakeholders both within the EU and globally in the field of microbial cultures, including meat fermentation applications [12].

Researchers worldwide focus on the use of starter cultures in meat product processing, including F. Toldrá, J. Arnau, G. Tabanelli, F.-K. Lücke, F. Leroy, V. Ferreira, L. Cocolin, M.-J. Chen, L. Vinnikova, L. Bal-Prylypko, and V. Pasichniy, among others.

This study **aims** to provide a theoretical synthesis and systematisation of data on the biochemical mechanisms of action of starter cultures in meat product technology.

Research materials and methods

The methodological framework was based on a systematic analytical review of recent studies on the use of starter cultures in meat product processing. The literature search was conducted in the international databases Scopus, Web of Science, and PubMed using combinations of the following keywords: «starter cultures», «meat products», «lactic acid bacteria», «protective cultures», «food cultures», «food safety», and «fermentation». The analysis included original research articles, reviews, and regulatory documents published in English and Ukrainian over the past two decades. Sources were selected based on their relevance, scientific contribution, and alignment with the research topic. The results were synthesised using systematic analysis, comparative analysis, and interpretation of the literature.

Analysis of recent research and publications

Humans have long used microorganisms in food production. Initially, these processes were not fully understood and were applied at an empirical level, where starter culture addition involved back-slopping (back-inoculation), i.e., the fermented product itself contained the microorganisms required to initiate fermentation in a new batch [13]. The next step involved the use of starter cultures for indirect inoculation, which requires the microorganisms to be activated and propagated in a specific culture medium prior to inoculation of the raw material. The main drawbacks of these starter cultures are linked to the high risk of contamination by bacteriophages and other microorganisms, the time-consuming and labour-intensive preparation process due to the requirement for 12 – 24 h of activation, the requirement for a separate room, specialised equipment and qualified staff, and the variability in the quality and storage stability of the

product [14]. A breakthrough in the use of starter cultures occurred in the 1970 s, thanks to advances in freezing, freeze-drying, and microbial concentration technologies. Highly concentrated forms of starter cultures (usually frozen or freeze-dried) have appeared on the market; these are added directly to the raw materials without prior activation or propagation in a culture medium, namely DVS (Direct Vat Set) and DVI (Direct Vat Inoculation). These starter cultures are widely used in the dairy, meat, and other food industries for the fermentation of products such as cheese, yogurt, and sausages and others [15].

The development of modern biotechnological methods, growing consumer demand for natural and environmentally friendly products, convenient ready-to-eat (RTE) meat products with innovative packaging, functional meat products, products with unique flavours, and the digitalization of production processes are opening up vast opportunities for the use of starter cultures that are adapted to specific technological characteristics and enable targeted control over key quality indicators of meat products. The global market for starter cultures in the meat industry is expected to exceed 106.3 million USD by 2033, with a compound annual growth rate (CAGR) of 4.3 % [16].

These factors, alongside globalisation and intense market competition, are prompting specialists in the meat processing industry to place strong emphasis on the application of starter cultures in several key areas:

– achieving high product safety standards;

– reproducibility and stability of the production process, as well as extended shelf life;

– enhancing nutritional value and producing products with functional properties.

From a biochemical perspective, fermentation plays a key role in these processes; it is a metabolic process in which adenosine triphosphate, essential for the growth and development of microorganisms, is produced via substrate-level phosphorylation under anaerobic conditions, without the release of CO_2. The end products depend on the specific microorganism, substrate and the enzymes that are present and active [17].

In the meat industry, starter cultures are used for fermentation, which mainly comprise lactic acid bacteria, coagulase-negative cocci (primarily staphylococcal species), moulds and yeasts [18]. These microorganisms can be used individually or as mixed cultures. Fig. 1 presents a generalised classification of starter cultures used in the meat processing industry.

It is difficult to summarise all available information on starter cultures and fermented meat products at this stage, as their production varies considerably across the world, employs different terminology, and has a complex historical and regional background, which complicates classification.

A wealth of scientific data is accumulating on fermentation processes and microbial taxonomy; consequently, various countries have developed their own lists of food cultures traditionally used in fermentation:

Denmark – Danish list of registered microbial cultures used in foodstuffs (last updated in 2016);

China – (1st list published in 2010 and regularly updated, food cultures);

EU – International Dairy Federation (IDF) and European Food and Feed Cultures Association (EFFCA);

FAO/WHO – bulletins No. 134 – Fermented fruits and vegetables, No. 138 – Fermented cereals, No. 142 – Fermented pulses, seeds and nuts [11]

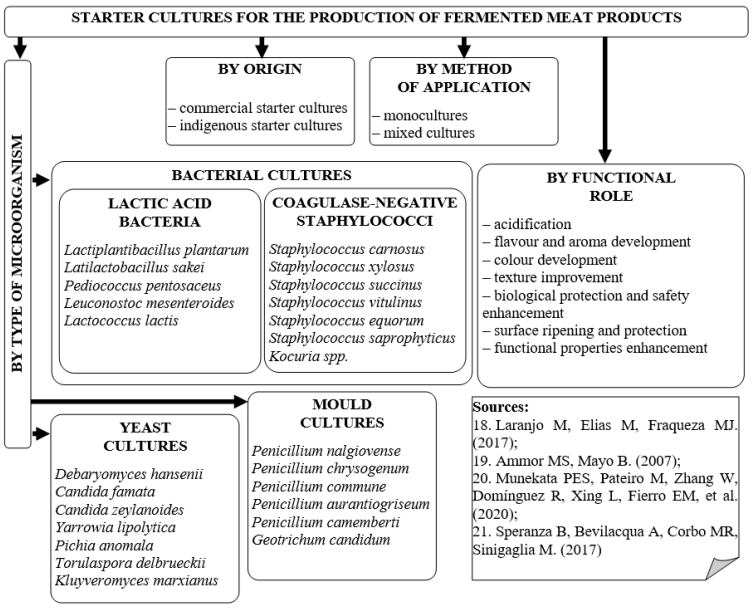

Fig. 1. Classification of starter cultures used in the production of fermented meat products

As of 2022, the European list of the International Dairy Federation included 58 types of microorganisms with proven safety profiles, which are used for fermentation in the meat processing industry [11].

Lactic acid bacteria are widely used in the production of fermented meat products; these are typically facultative anaerobes and belong mainly to the genera *Lactobacillus* spp., *Leuconostoc*, *Pediococcus*, *Lactococcus*, *Enterococcus*, *Oenococcus* and *Streptococcus*. Other facultative anaerobes used in the production of fermented sausages include *Staphylococcus xylosus*, *Staphylococcus carnosus*, *Staphylococcus equorum*, and *Staphylococcus saprophyticus*. Aerobic bacteria of the family *Micrococcaceae*, such as *Kocuria* spp., are also used in sausage production. Yeasts are starter cultures that can exhibit aerobic or facultative anaerobic metabolism. The most commonly used species are *Debaryomyces* spp. and *Candida* spp. Moulds, being strict aerobes, are inoculated onto the surface and belong mainly to the species *Penicillium nalgiovense* and *Penicillium gladioli*. Traditionally, these cultures are added to meat products at high concentrations (10^7 – 10^8 CFU/g) to ensure the fermentation process proceeds as required [21].

The safety of fermented meat products. Meat and meat products are complex systems with high perishability due to a wide range of factors, including the activity of endogenous enzymes in fresh meat, microbial growth, and oxidation processes. Pathogenic microorganisms, including *Listeria monocytogenes*, *Staphylococcus aureus*, *Escherichia coli*, *Clostridium perfringens*, and *Salmonella* spp., can cause foodborne diseases in humans. Furthermore, microbial growth during storage is a key factor contributing to product spoilage and, consequently, economic losses [22]. Heat-treated meat products have lower levels of microbial contamination. In addition, chemical compounds such as biogenic amines, mycotoxins, nitrosamines, and polycyclic aromatic hydrocarbons may accumulate in meat products, posing a risk to human health.

The safety of fermented meat products produced using starter cultures results from the synergistic action of biochemical mechanisms that form a multi-level protective system. Lactic acid bacteria (LAB) are essential components of this system. By exploiting the properties of these microorganisms, humans have used them for many years in the production of fermented dairy products, the leavening of bread dough, fermented vegetables, and fermented meat products [23, 24]. The metabolites produced by LAB during substrate degradation alter the properties of the product and inhibit the growth of competing microflora that can otherwise lead to spoilage. Such antimicrobial metabolites include organic acids (lactic, pyruvic, benzoic, oleic, and β-phenyl lactic acids), acetone, diacetyl, phenylethylamine, bacteriocins (classes I – IV), low-molecular-weight organic compounds (reuterin, reutericyclin, etc.), hydrogen peroxide (H_2O_2), CO_2, and others [25, 26]. The antimicrobial compounds produced by LAB are widely applied in food preservation at the industrial scale [27].

LAB are part of the natural microflora developing in meat after slaughter. In fresh meat, they facilitate a mild fermentation process without altering the sensory characteristics, due to the low carbohydrate content and strong buffering capacity of meat [28]. Furthermore, LAB constitute the majority of starter cultures. The most important species include *Lactobacillus sakei*, *Lactobacillus curvatus*, *Lactobacillus plantarum*, and *Pediococcus pentosaceus*. Their role in ensuring microbiological safety is ensured through multiple parallel mechanisms. The first and most important mechanism is the fermentation of fermentable carbohydrates and the rapid accumulation of undissociated organic acids (acetic and lactic acids), leading to a decrease in pH. Organic acid molecules diffuse through the cell membrane, where they dissociate, leading to a collapse of the proton motive force. This disrupts transport systems and results in microbial cell death, thereby inhibiting spoilage and reducing the risk of foodborne illness. A pH reduction below 5.3 during the first 24 – 48 hours of fermentation inhibits the growth of *Enterobacteriaceae* and pathogens such as *Staphylococcus aureus* [29].

In addition to acidifying the product, LAB produce bacteriocins. These are typically positively charged molecules exhibiting pronounced hydrophobicity and capable of interacting with negatively charged components of microbial cell membranes, such as the phosphate groups of phospholipids and specific receptors located in the bacterial cell wall. This results in the inhibition of nucleic acid and protein synthesis in pathogenic microorganisms and the destabilisation of the cytoplasmic membrane. Furthermore, bacteriocins can form pores in the cell membranes of target bacteria, leading to disruption of ion homeostasis, alteration of intracellular pH, and leakage of intracellular contents. However, bacteriocins are characterized by a relatively narrow antimicrobial spectrum, as they primarily inhibit microorganisms that are phylogenetically related to the producer strain, including closely related bacterial species and genera [30, 31].

Bacteriocins are currently classified based on several characteristics, including molecular weight, antimicrobial spectrum, mechanism of action, thermal stability, amino acid composition, and post-translational modifications. Bacteriocins can also be classified into two main groups: those produced by Gram-positive bacteria and those produced by Gram-negative bacteria [32]. Based on their biochemical and genetic characteristics, LAB bacteriocins are classified into three classes. Class I consists of thermostable, post-translationally modified peptides with molecular weights below 5 kDa. Class II includes thermostable, unmodified peptides with molecular weights below 10 kDa, whereas Class III comprises high-molecular-

weight thermolabile proteins with molecular weights exceeding 10 kDa. Bacteriocins belonging to Classes I and II are the most widespread [33].

Only certain groups of bacteriocins have been applied in the production of meat and meat products, as they retain their activity over a range of storage temperatures and exhibit high stability in the complex protein – fat matrix of meat.

Lactococcus lactis produces the bacteriocin nisin, which exhibits antibacterial activity against a broad spectrum of Gram-positive bacteria, including *Staphylococcus* spp., *Pediococcus* spp., and *Listeria monocytogenes*, as well as certain Gram-negative bacteria, such as *Escherichia coli*, *Helicobacter pylori*, and *Acinetobacter baumannii*. Nisin is widely used as an antimicrobial agent for controlling a broad spectrum of foodborne pathogens associated with meat, dairy, and fish products. In certain food systems, nisin retains its activity even after pasteurisation, sterilisation, and other thermal processing treatments. Nisin remains stable under low pH (acidic) conditions. Nisin is a peptide consisting of 34 amino acids, with a molecular weight below 5 kDa, and belongs to Class I bacteriocins [34, 35, 36]. The near-neutral pH of meat products (5.6 – 6.2) and the presence of glutathione, which can interact with nisin and thereby reduce its antimicrobial activity, may limit the use of nisin in meat processing. However, nisin is widely used to inhibit the growth of *Clostridium botulinum* and *Bacillus cereus* in pasteurised and vacuum-packed meat products [37]. Nisin is rapidly degraded in the human digestive tract, thereby minimising the risk of adverse effects on consumers [38].

The bacteriocins produced by *Lactobacillus sakei* and *Lactobacillus curvatus*, known as sakacins, are of particular interest as they belong to Class II bacteriocins. The best-characterised sakacins are sakacin A, G, K, P, and Q. Current research is focused on determining their effectiveness in controlling the growth of pathogens such as *Listeria monocytogenes*, *Enterococcus* spp., and *Brochothrix thermosphacta* in fermented meat, sausage, cheese, and other fermented products. The combination of sakacin G and P produced by *L. sakei* CWBI-B1365 and *L. curvatus* CWBI-B28, respectively, showed synergistic inhibition of *Listeria monocytogenes* in chicken and beef [39, 40]. Two strains of *Lactilactobacillus curvatus*, isolated from an italian-type salami, produce the bacteriocins sakacin P and sakacin X, which are active against *Listeria monocytogenes*. Furthermore, the addition of these semi-purified bacteriocins to the salami meat batter resulted in a 2-log 10 reduction in *Listeria monocytogenes* counts (CFU/g) in the final product [41]. Sakacins remain stable under low-temperature fermentation conditions and salting and are effective in extending the shelf life of beef and poultry [42, 43]. Like nisin, sakacins are sensitive to pepsin and trypsin [44].

Species of the genus *Pediococcus*, including *P. acidilactici*, *P. claussenii*, *P. cellicola*, *P. damnosus*, *P. ethanolidurans*, *P. inopinatus*, *P. parvulus*, *P. pentosaceus*, and *P. stilesii*, produce pediocin, a class II bacteriocin with a molecular weight below 5 kDa. These bacteriocins exhibit antimicrobial activity against Gram-positive bacteria, especially *Listeria monocytogenes*. A distinctive feature of pediocins is their bactericidal activity, which is retained under a wide temperature range, including high temperatures associated with thermal sterilisation processes and storage at - 80 °C. In addition to thermal stability, pediocins remain active across a broad pH range (2 – 10) [45, 46, 47]. There are two methods for introducing bacteriocins into a food matrix: (I) inoculating the matrix with a bacteriocin-producing strain and allowing in situ production of the antimicrobial peptide; and (II) directly adding the pre-synthesised bacteriocin [48]. In 1997, researchers at state university Oregon [49] found that powdered pediocin applied to plastic meat packaging bags reduced the growth of *Listeria monocytogenes* at 4 °C over a 12-week storage period. Pediocins are non-toxic to humans and are rapidly degraded in the gastrointestinal tract, supporting their potential use in food technology [50].

Another genus within the LAB group, *Enterococcus* spp., produces enterocins. These bacteriocins are difficult to classify, as they share characteristics of one or more bacteriocin classes and subclasses [26, 51]. Enterocin inhibits the growth of foodborne pathogens in meat products, including *Listeria monocytogenes*, *Salmonella* spp., and *Escherichia coli*. Enterocin AS-48 has been registered and exhibits a broad spectrum of antibacterial activity. It can be used as a food additive, and has shown no mutagenic or haematotoxic effects [52]. Several *Enterococcus* species are used as starter cultures in non-thermally processed (fermented) meat products. For example, *E. faecium*, *E. mundtii*, and *E. casseliflavus* are applied in the production of fermented meat products [53, 54, 55]. The effect of enterocins produced by *Enterococcus faecium* CTC492 resulted in a 7.98-log10 reduction in *Listeria* counts in cooked ham. In chicken breasts stored at 7 °C for 7 days, a 5.26-log10 reduction was observed compared with the control [56].

However, the use of *Enterococcus* spp. in food technology remains controversial due to the potential for horizontal transfer of antibiotic resistance genes, the presence of virulence factors, and biogenic amine production. Therefore, controlling these bacteria is crucial for food safety. According to the European Food Safety Authority (EFSA), each *Enterococcus* spp. strain requires individual genomic characterisation, and only strains with demonstrated safety may be included in the Qualified Presumption of Safety (QPS) list [57, 58].

In 1991, a group of canadian and american scientists first isolated a bacteriocin produced by *Leuconostoc gelidium* strain UAL 187, which was

designated leucocin A [59]. Leucocin, a Class II bacteriocin produced by *Leuconostoc* spp., can be used as a natural preservative in fermented food products. Leucocin A and Leucocin C have been shown to be effective against *Listeria monocytogenes* in various food products. The addition of *Leuconostoc carnosum* 4010 strain, which produces leucocin C, to vacuum-packed sausages reduced *Listeria monocytogenes* counts to <10 CFU/g after 21 days of storage at 5 °C [60, 61, 62].

Although scientific literature contains information on the safety of lactic acid bacteria (LAB) bacteriocins for consumers, nisin is the most strictly regulated bacteriocin globally and is approved for use in many countries. In the European Union (EU), the use of bacteriocins is regulated under Regulation (EU) No 1333/2008 on food additives. Nisin is listed as the food additive E 234. In 2017, the EFSA re-evaluated its safety and authorised its use in heat-treated meat products at concentrations of up to 25 mg/kg. An acceptable daily intake (ADI) of 1 mg/kg body weight has also been established [63]. In the USA, the use of bacteriocins is regulated under the GRAS (Generally Recognized as Safe) framework of the United States Food and Drug Administration (FDA). The USA approach is more flexible, as it permits the use of bacteriocins as specialised protective cultures or processing aids. In the United States, nisin is recognised as an antimicrobial agent considered safe for use in food [64].

Currently, only the use of nisin (INS 234) as a preservative is regulated at the international level [65]. Other bacteriocins (pediocin, enterocins, leucocins) are currently used primarily as part of starter or protective cultures and do not have a distinct internationally harmonised regulatory status.

LAB also produce low-molecular-weight antimicrobial metabolites, which are regarded as promising agents for the biological preservation of meat and meat products due to their antifungal activity [66]. In meat products, fungi can develop during cold storage and affect the appearance, taste and texture of the products and may cause foodborne illness in consumers. Such spoilage can be caused by species of the genera *Penicillium*, *Aureobasidium*, *Thamnidium*, *Candida*, *Cryptococcus* and *Yarrowia* [67, 68]. Certain strains of *Lactobacillus reuteri* are capable of producing reuterin, which is a multi-component system comprising 3-hydroxypropionaldehyde (3-HPA), 3-HPA hydrate, 3-HPA dimer, and acrolein. Another metabolite is reutericyclin, a derivative of tetramic acid. The production of reuterin and reutericyclin depends on the genetic background of the strain and environmental conditions. They exhibit antimicrobial activity against a wide range of Gram-positive and Gram-negative bacteria, yeasts, moulds and protozoa by reducing free thiol groups in glutathione, proteins and enzymes, thereby disrupting cellular redox homeostasis and leading to cell death. In vitro studies have demonstrated that reuterin exhibits antifungal activity at concentrations ranging from 4 to 10 mmol/dm³. Numerous studies demonstrate the significant potential of reuterin as a food preservative but do not elucidate its interactions with food products, highlighting the need for further in-depth research, as the increased reactivity of the aldehyde group and the formation of acrolein at elevated temperatures may affect the sensory properties and safety of foods [69, 70, 71, 72, 73, 74]. There is currently a lack of scientific studies on the application of reutericyclin in food technology.

Spanish researchers [19] reported that most lactic acid bacteria (LAB) can produce hydrogen peroxide under aerobic conditions through the action of flavoprotein oxidases or NADH oxidase. Pathogenic bacteria such as *Pseudomonas* spp. and *Staphylococcus aureus* are highly susceptible to H_2O_2 due to enzyme denaturation caused by oxidation of sulfhydryl groups and increased membrane permeability resulting from lipid peroxidation. Hydrogen peroxide (H_2O_2) is particularly effective at the early stages of fermentation. However, it should be noted that the accumulation of H_2O_2 in fermented meat products may pose a technological risk, as even low concentrations can trigger a cascade of pigment, lipid and protein oxidation. Therefore, controlling fermentation parameters and selecting starter cultures with catalase activity represents a key strategy for preventing undesirable changes [75].

Another group of microorganisms widely used as starter cultures in the meat industry are coagulase-negative staphylococci (CNS), among which the most common are *Staphylococcus carnosus* and *Staphylococcus xylosus*. CNS have a broad impact on the properties of meat products, including product safety. They contribute to improving the shelf life of meat products by catalysing the synthesis of nitric oxide (NO) from L-arginine via the enzyme nitric oxide synthase. Nitric oxide (NO) is highly reactive and contributes to microbial safety in meat products by inhibiting the growth of microorganisms such as *Clostridium botulinum*, while also enhancing flavour and colour [76]. In meat products, added nitrate salts are reduced to nitrite via the nitrate-reducing activity of staphylococci. Experimental studies on meat curing have shown that inoculation with *Staphylococcus xylosus* reduces nitrate concentrations by more than 80 % after 24 hours of incubation, which is beneficial from a consumer safety perspective, as nitrate is toxic to human health. Thus, owing to their nitrate reductase activity, CNS contribute to reducing nitrite content in the final product [77, 78, 79]. Residual concentrations in the final product are regulated by a European Union regulation that has been transposed into Ukrainian legislation and range, for heat-treated meat, from 100 to 150 mg/kg of nitrite, while for unprocessed meat, limits

of 150 mg/kg of nitrite and 150 mg/kg of nitrate are permitted [80].

During fermentation of meat products, moderate lipid oxidation occurs. This process is technologically important for flavour and colour development; however, excessive oxidation may pose a risk to consumer health. The most common product of lipid peroxidation is malondialdehyde, which under in vitro conditions can modify proteins, DNA, RNA, and other biomolecules. Some strains of CNS can reduce lipid oxidation in meat products. These include *Staphylococcus xylosus*, *Staphylococcus carnosus*, *Staphylococcus cohnii* and certain strains of *Staphylococcus saprophyticus*. According to [81], this is due to the production of catalase and superoxide dismutase, reduced levels of reactive oxygen species, the breakdown of H_2O_2, inhibition of lipoxygenase activity, and reduced accumulation of secondary oxidation products. It has been established that the reduction in malondialdehyde (MDA) content in fermented sausages following the addition of CNS ranges between 15 % and 40 %, depending on the strain, formulation and ripening time.

French researchers [82] reported that CNS are adapted to oxidative stress conditions and described antioxidant systems based on catalase and superoxide dismutase, which reduce reactive oxygen species accumulation and limit lipid oxidation in the presence of *Staphylococcus xylosus* The antioxidant activity is strain-dependent, and not all CNS exhibit the same level of effectiveness in inhibiting lipid oxidation. Thus, the metabolic heterogeneity among CNS strains is currently a focus of research, enabling the selection of strains with improved antioxidant properties for lipid quality and stability control in meat products [81, 83]. Recent studies have shown that increased levels of lipid oxidation products in fermented sausages are associated with increased histamine production [84]. Consequently, biogenic amine accumulation can be reduced by controlling lipid oxidation during processing, thereby improving the safety of the final product.

Another major functional group of starter cultures used in meat production consists of yeasts and moulds [21]. Their impact on meat product safety is both positive and negative, depending on the type of microorganism, production conditions and fermentation control. The most commonly used strains are *Debaryomyces hansenii*, *Hyphopichia burtonii* and some *Penicillium* spp.

Yeasts are a constant component of the microbial microbiota in traditional meat products, and their concentration ranges from 10^3 to 10^7 CFU/g during ripening. The most common species used as starter or protective cultures is *Debaryomyces hansenii*, owing to its ability to grow at high NaCl concentrations and at low water activity.

Debaryomyces hansenii is used as a biopreservative capable of reducing biogenic amines and inhibiting the synthesis of mycotoxins and the growth of undesirable moulds. Inoculation with the yeast *Debaryomyces hansenii* limits lipid oxidation and prevents nitrite oxidation during drying. The yeast produces a complex of antioxidant enzymes, including superoxide dismutase, catalase, and glutathione peroxidase. These enzymes neutralise reactive oxygen species generated during metabolism or upon exposure to light. In addition, during aerobic growth on the surface or in near-surface layers of meat products, yeast actively depletes residual oxygen. The use of specific strains, such as Y61 and Y67, reduces lipid oxidation by 36 – 40 % compared to non-inoculated samples [85].

The conditions during meat product maturation are conducive to the growth of toxigenic mould on their surface, posing a risk of mycotoxin production and accumulation. Aflatoxins and ochratoxin A are most frequently detected in dried meat products. The yeast *Debaryomyces hansenii* can inhibit the growth of two ochratoxin A-producing fungi, *Penicillium nordicum* and *Penicillium verrucosum*, and a reduction in ochratoxin A production and accumulation in the product has been observed. Three main mechanisms underlying yeast antifungal activity have been identified: competition for nutrients within the microbial ecosystem; the production of antifungal volatile compounds; and the production of mycocins. The maximum inhibitory effect of *Debaryomyces hansenii* against various spoilage and pathogenic microorganisms was observed at an NaCl concentration of 8 %. It has been established that inoculation with *Debaryomyces hansenii* can result in the complete inhibition of *Enterobacteriaceae* in fermented sausages, due to competition for nutrients and sugars, as well as changes in physicochemical parameters (a_w, and pH) of the medium [86, 87].

Debaryomyces hansenii has QPS status granted by the EFSA [88]. The potential risk associated with the use of yeast in meat product fermentation is related to the need for careful selection of specific strains and their prior characterization.

During dried meat product production, there is a risk of mould genera such as *Alternaria*, *Aspergillus*, *Cladosporium*, *Eurotium*, *Mucor*, *Penicillium*, *Rhizopus*, and *Scopulariopsis* developing on the surface. The main danger associated with mould growth is the proliferation of wild-type toxigenic strains that produce mycotoxins, including ochratoxin A, aflatoxins, patulin, and cyclopiazonic acid, among others [89]. The use of mould starter cultures, primarily belonging to the genus *Penicillium*, is a crucial step in the production of many types of dry-cured sausages (such as salami and salchichón) and cured meats. They are applied to the surface of the product by dipping in or spraying with a spore suspension. The most important species are *Penicillium nalgiovense* and *Penicillium chrysogenum*, which are valued for forming a uniform white surface layer and providing effective protection against

undesirable microbial growth. These starter cultures act as agents of competitive exclusion. By rapidly colonising the sausage casing, they occupy the surface of the meat product, thereby limiting nutrient availability and colonisation space for undesirable microorganisms such as *Penicillium nordicum* and *Aspergillus* spp. [90].

However, one aspect of its impact on food safety that remains controversial is whether certain strains of *Penicillium nalgiovense* are capable of producing penicillin. Although antibiotic residues are rarely detected in finished products after ripening, due to penicillinase activity and processing conditions, there is still a potential risk for individuals with a penicillin allergy. Strain selection and genetic engineering approaches have been developed to overcome this limitation. Modern commercial starter cultures undergo rigorous testing to ensure that they do not contain genes encoding the synthesis of not only antibiotics but also major foodborne mycotoxins, including aflatoxins, ochratoxin A, and patulin [91].

The use of moulds in food production, as is the use of yeasts, is regulated by international organizations. Key concepts in this context are the QPS status granted by EFSA and the GRAS status established by the FDA. For moulds such as *Penicillium nalgiovense*, QPS or GRAS status is not automatically granted due to their phylogenetic relatedness to toxigenic species. Therefore, starter culture manufacturers are required to demonstrate the absence of mycotoxin production in specific production strains and provide detailed supporting evidence [92].

The modern approach to ensuring the safety of fermented meat products is based on the synergistic effects of distinct microbial groups, with yeasts and moulds complementing the activity of LAB and CNS. This comprehensive approach, known as «hurdle technology», enables the production of microbiologically safe meat products with minimal use of chemical preservatives [93].

The effect of starter cultures on process stability and the shelf life of fermented meat products. A key requirement of modern industrial production of fermented meat products is the manufacture of finished products with standardised characteristics in every batch. The spontaneous fermentation of traditional products relies on the indigenous microflora of the raw materials and the surrounding environment; however, this approach is associated with a high risk of production failures, instability in sensory characteristics, and the potential growth of pathogens. Conversely, the introduction of selected starter culture strains enables the standardisation of production cycles and ensures the reproducibility of the ripening process [94].

LAB is the dominant group due to its exceptional ability to adapt to the specific environment of minced meat, which is characterised by high levels of protein, fat, salt, sodium nitrite, and other constituents. The metabolic activity of LAB is classified into homo- and heterofermentative types. Homofermentative species convert glucose almost exclusively into lactic acid, resulting in a sharp decrease in pH without the formation of gaseous by-products, which is critical for product quality. Heterofermentative bacteria use the Emden–Meyerhof–Parnas pathway and produce acetic acid, ethanol, and carbon dioxide [95].

The rate of pH decline is a critical factor that not only determines product safety due to the formation of organic acids but also contributes to the development of a range of sensory characteristics and facilitates the drying process. LAB starter cultures are added at a concentration of 10^6 – 10^7 CFU/g, which promotes active carbohydrate metabolism. During the first 24 – 48 hours of fermentation, the pH decreases from 5.8 – 6.0 down to the isoelectric point of most meat proteins (around 5.1 – 5.3) and, in some cases, to 4.6 – 4.8. This leads to coagulation of sarcoplasmic and myofibrillar proteins and the formation of a denser structure due to the release of free water, thereby reducing the water activity (a_w) of fermented sausages. The initial aw in meat is 0.96 – 0.98 and decreases to 0.85 – 0.92 in semi-dry products and below 0.85 in dry products as a result of dehydration and NaCl addition. The combination of low pH and low a_w values ensures microbiological stability even under ambient temperature conditions. However, under these conditions, the fermentation process must be carefully monitored to determine the optimal time to start drying, in order to avoid surface toughening of the product or loosening of the mince structure. When LAB starter cultures are used, this phase transition occurs in a controlled manner. Proteolysis is initiated by endogenous enzymes, particularly cathepsins (especially cathepsin D), which degrade myofibrillar and sarcoplasmic proteins into high-molecular-weight peptides; during subsequent maturation stages, microbial peptidases play a dominant role. Studies have shown that Lactobacillus sakei strains exhibit the highest proteolytic activity among LAB, exceeding that of *Lactobacillus curvatus* and *Pediococcus acidilactici*. The use of starter cultures results in improved hardness, elasticity, and chewiness in the finished product compared to spontaneously fermented products [19, 96, 97].

Simultaneously, lipolysis occurs, leading to accumulation of free fatty acids, which are precursors of many aromatic compounds. Microbial lipases from CNS and yeasts are particularly active. Lipases from *Debaryomyces hansenii* are crucial for the development of the characteristic flavour of the finished product, while *Staphylococcus xylosus* influences aroma formation by converting free fatty acids into ketones and aldehydes and limiting excessive oxidation, thereby preventing the development of off-flavours such as rancidity [98, 99, 100]. The authors [101] report that

Debaryomyces hansenii influences the development of a smoky aroma in fermented sausages.

Starter cultures play a key role in aroma formation by converting free amino acids into volatile aroma compounds. The catabolism of branched-chain amino acids – leucine, isoleucine, and valine – is essential for this process. In the presence of starter cultures, particularly by *Staphylococcus xylosus*, leucine undergoes transamination to α-ketoisocaproic acid, which is subsequently decarboxylated to form 3-methylbutanal – a key aroma compound with malty, nutty, and chocolate notes. 3-Methylbutanal can be further reduced to 3-methylbutanol or oxidized to 3-methylbutanoic acid (isovaleric acid). The formation of 3-methylbutanoic acid predominates, whereas 3-methylbutanol formation is less pronounced and depends on fermentation conditions and strain type [102, 103]. The co-application of Staphylococcus xylosus A2 and Lactobacillus plantarum R2 significantly increases the content of volatile compounds responsible for the characteristic aroma of fermented sausages [104].

The colour of fermented meat products depends on the chemical state of myoglobin. During fermentation, CNS nitrate reductases reduce nitrate to nitrite, which is further reduced to nitric oxide that reacts with myoglobin to form nitrosylmyoglobin. CNS strains *Staphylococcus carnosus* and *Staphylococcus xylosus* produce catalase and other enzymes that scavenge reactive oxygen species, thereby reducing the redox potential (Eh) of the product and stabilizing nitrosylmyoglobin [101]. CNS nitrite reductase activity is crucial as it determines colour intensity and stability, the bacteriostatic effect of nitrite, and the residual nitrite level in the finished product.

The mechanisms by which starter cultures influence the safety parameters of the final product have been discussed above and show that they form effective barriers to the growth of pathogenic microorganisms via a rapid decrease in pH, bacteriocin production, competitive exclusion, and other inhibitory mechanisms. However, prolonging the shelf life of fermented meat products requires additional preservation methods, including vacuum packaging, modified atmosphere packaging (MAP), and novel packaging materials. Researchers from Croatia [105] investigated the microbiological, physicochemical, and sensory characteristics of industrially produced dry fermented sausages using starter cultures composed of *Lactobacillus plantarum* (25 %), *Pediococcus pentosaceus* (25 %), and *Staphylococcus xylosus* (50 %), during storage under vacuum and in a 100 % nitrogen (N_2) atmosphere for 120 days at 4, 22, and 37 °C. It has been shown that there was no increase in microbial load during storage, and the shelf life was limited by changes in sensory parameters, amounting to 95 days at 4 °C (under vacuum) and more than 120 days under modified gas storage (MAP), and 30 and 40 days, respectively, at 22 °C. At 37 °C, all samples remained suitable for consumption for only 15 days.

Korean researchers [106] found that vacuum packaging is less effective than MAP during storage of fermented sausages at 4 °C for 45 days. They analysed four MAP gas mixtures: 1 – 25% CO_2 / 75% N_2; 2 – 50% CO_2 / 50% N_2; 3 – 70% CO_2 / 30% N_2; 4 – 100% CO_2. Monitoring the accumulation of lipid oxidation products showed that all MGS packaging options were more effective, and that malondialdehyde accumulation during storage is inversely proportional to CO_2 concentration in the MAP. In addition, it has been demonstrated that the presence of CO_2 in the system inhibits Gram-negative bacteria, including anaerobic and facultative anaerobic species such as *Escherichia coli* O157:H7 and *Salmonella* spp.

At the same time, European researchers [107] argue that vacuum packaging is suitable for extending the shelf life of fermented sausages, provided that selected starter culture strains – comprising *Lactobacillus sakei*, *Staphylococcus carnosus*, *Staphylococcus xylosus*, *Pediococcus pentosaceus*, and *Debaryomyces hansenii* in lyophilized form – are used. This method allows extending the shelf life of Sardinian-type fermented sausages to 120 days at 4 ± 1 °C without significant changes in their microbiological, physicochemical, and sensory characteristics. However, the authors report that even with vacuum packaging, the risk of contamination with the pathogen *Listeria monocytogenes* is not fully eliminated. To prevent *Listeria monocytogenes* infection, strict control of sanitary conditions in production is essential.

Multilayer films from different polymer classes are used for packaging fermented meat products to achieve high-barrier properties. Each layer serves a specific function, ranging from providing mechanical strength and heat sealability to creating a virtually impermeable barrier to gases and moisture. For long-term storage of dry sausages under vacuum or MAP, structures based on polyamide, polyethylene terephthalate, polyvinyl chloride, linear low-density polyethylene, ethylene-vinyl alcohol, among others, have been shown to be among the most effective. However, the presence of heterogeneous materials in the film structure complicates or prevents recycling [108].

Packaging of whole and sliced portioned meat products involves significant differences in the dynamics of physicochemical processes during storage [109]. For dry fermented sausages, the production of which involves the formation of a protective layer of the noble mould *Penicillium nalgiovense* on the casing, the use of hermetic high-barrier vacuum packaging or oxygen-free conditions is unacceptable. Oxygen deprivation inhibits mold metabolism, leading to mycelial death and autolysis, the development of undesirable dark casing coloration, and putrid off-odour. In contrast, when fermented meat products are

sliced, the surface area exposed to the environment increases severalfold, significantly accelerating lipid oxidation and nitrosomyoglobin degradation [110, 111].

Most studies on the application of innovative packaging technologies in meat processing focus on meat products as a whole, while limited information is available on fermented meat products characterized by low pH and a_w levels. Modern consumers pay close attention to the presence of synthetic additives in fermented meat products, and packaging materials, although not consumed, may also have a negative environmental impact. Therefore, the development of alternative packaging technologies specifically for fermented meat products remains a pressing issue. Researchers from Serbia [112] have proposed the use of a bilayer coating composed of chitosan and caraway essential oil aimed at extending the shelf life of a traditional dry-fermented sausage (Petrovská klobása), which differs from the traditional formulation by the inclusion of the starter culture CNS *Staphylococcus xylosus*. The first layer, in contact with the product surface, consists of a chitosan matrix emulsified with caraway essential oil, which functions as a natural antioxidant. The second, outer layer comprises a mixture of chitosan and beeswax and serves as a barrier against moisture migration. According to the authors, this approach slows moisture loss and reduces lipid oxidation by over 20 %. The coating also helps the sausage retain its characteristic aroma. However, practical application under industrial production and commercial conditions requires further investigation. Despite rapid developments in this field, the development of eco-friendly packaging materials with high barrier performance for fermented meat products has not been sufficiently investigated.

Effects of starter cultures on the nutritional and biological properties of fermented meat products. Scientific research over the past two decades has substantially reshaped understanding of the role of starter cultures, from performing purely technological functions to exerting a systemic impact on the nutritional and biological properties of the final product. These microorganisms participate in key biochemical processes, including proteolysis, lipolysis, and the synthesis of bioactive compounds, vitamins, and antioxidants, while also contributing to the formation of undesirable metabolites, particularly biogenic amines [113]. Proteolysis is the primary biochemical process involved in the maturation of fermented meat products. The final stages of proteolysis, namely the hydrolysis of oligopeptides into short peptides and free amino acids, predominantly essential amino acids such as phenylalanine, isoleucine, and leucine, are catalyzed by peptidases and proteases produced by starter cultures, primarily by strains belonging to *Lactobacillus sakei*, *Lactobacillus plantarum*, and *Staphylococcus xylosus*. During the ripening process, the content of non-protein nitrogen increases significantly, serving as an indicator of the degree of proteolysis [99]. Proteolysis enhances protein digestibility, since the fermented product contains readily digestible nitrogenous compounds, thereby reducing digestive load and increasing the nutritional and biological value of the product [114, 115]. Excessive protein degradation leads to the accumulation of bitter peptides and amino acids, particularly hydrophobic peptides rich in leucine, proline, and valine, resulting in bitterness development and potentially impairing product digestibility in the gastrointestinal tract [116].

Extensive research is currently being conducted on probiotic microorganisms in starter culture systems. Researchers [117] have proposed the use of a combination of *Lactobacillus plantarum* and *Lactobacillus acidophilus* in starter cultures for proteolysis of proteins. It has been shown that the addition of *Lactobacillus acidophilus*, either alone or in combination with other strains, does not affect the sensory properties of the product, while changes in the physicochemical properties of the meat matrix occur via mechanisms similar to those observed with other standardized LAB strains. This approach enables the production of products with probiotic characteristics, thereby enhancing their market competitiveness and appealing to health-conscious consumers. The introduction of probiotic starter cultures in meat processing is a complex, multi-stage, and resource-intensive process requiring expertise in microbiology, food technology, and medical sciences [118].

Researchers from Spain [119] also note that extensive proteolysis of muscle proteins releases bioactive peptides with antihypertensive and cardioprotective properties. The study [120] provides an overview of bioactive peptides in fermented meat products. These peptides may play an important role in antioxidant and anti-inflammatory activities and inhibit angiotensin-converting enzyme and dipeptidyl peptidase IV. During fermentation, changes in the fat fraction of the product lead to an increase in the content of free fatty acids. Studies [121] have shown that starter cultures comprising *Lactobacillus sakei*, *Staphylococcus carnosus*, *Staphylococcus xylosus*, and *Pediococcus pentosaceus* in turkey sausages exert a complex influence on lipid fraction dynamics. After 120 days of storage, oleic, linoleic, linolenic, and palmitic acids were identified in the sausages. The oleic acid content increased from 1.77 % – 1.99 % to 6.56 % – 13.01 % of total fatty acids, which can lead to both an increase in the biological value of the lipid fraction of fermented sausages and increased susceptibility to oxidative rancidity.

The synthesis of γ-aminobutyric acid (GABA) by certain LAB strains during fermentation is of particular interest. GABA is the primary inhibitory neurotransmitter in the central nervous system and exhibits antihypertensive, antidiabetic, and anxiolytic activities [122]. Four strains exhibiting GABA

production levels ranging between 7,339 and 9,060 mg/dm^3 have been identified in the traditional Thai fermented sausage *nham*: *Pediococcus pentosaceus* (HN8, NH102, NH116) and *Lactobacillus namurensis* (NH2) [123]. However, systematic research on GABA synthesis in European fermented sausages remains limited, highlighting a promising direction for future scientific investigation.

Challenges and issues. An analysis of accumulated scientific data indicates that the safe and effective application of starter cultures in fermented meat production requires addressing a complex range of interrelated biological and technological challenges. Despite their advantages, significant challenges remain that directly affect the safety, stability, and quality of the final product.

Of particular concern are the hidden risks associated with the spread of antibiotic resistance through food products, which may pose a substantial burden on healthcare systems. Starter culture microorganisms, including both LAB and CNS, often carry resistance genes to tetracyclines, penicillins, macrolides, and chloramphenicol. The high density of microbial populations and intense cell-cell interactions within the confined space of the meat matrix create favourable conditions for horizontal gene transfer from technological strains to pathogenic microorganisms or members of the consumer's resident gut microbiota [124]. The EFSA has established safety standards requiring manufacturers to perform comprehensive genetic screening of starter cultures for transferable antibiotic resistance genes. The use of databases such as CARD (Comprehensive Antibiotic Resistance Database) [125] allows the identification and exclusion from industrial use of strains carrying undesirable genetic elements, thereby contributing to the biosafety of food products.

Another challenge is related to bacteriophage contamination, which may be either indigenous or exogenous. When introduced from the external environment, bacteriophages follow the classical lytic cycle and can proliferate rapidly during fermentation processes involving starter cultures. Even a small initial phage load can result in a complete arrest of LAB metabolic activity within several hours. The induction of the lytic cycle in lysogenic strains carrying integrated prophages can occur under specific conditions. Under normal conditions, the prophage remains in a repressed state within the bacterial genome. During induction from lysogeny to the lytic cycle, the bacterium undergoes lysis, releasing phages that infect neighbouring cells lacking prophages. This may lead to «unexplained» culture collapse even under apparently sterile conditions. This situation can be mitigated through a comprehensive approach that includes the use of phage-resistant strains, rotation of starter cultures, avoidance of lysogenic strains, and careful monitoring of the production environment [126].

Certain challenges may arise when using CNS [127]. Their technological value (nitrate reductase activity, antioxidant properties, and aroma formation) is well established; however, safety concerns persist. Some CNS strains are capable of producing staphylococcal enterotoxins, which are heat-stable and capable of causing food poisoning. In addition, they may produce decarboxylase enzymes capable of converting free amino acids into biogenic amines (e.g., tyramine, histamine, and putrescine). Further safety concerns include their potential for high antibiotic resistance and their ability to form biofilms, both of which represent critical issues in the production of fermented meat products.

The use of starter cultures in the meat industry carries significant risks, including the spread of antibiotic resistance genes, bacteriophage contamination, and the ability of certain strains to produce toxins and biogenic amines. To minimize these risks, manufacturers must transition from empirical strain selection to comprehensive genomic and metabolic characterization of microbial cultures, use phage-resistant strains, and ensure rigorous monitoring of production processes. A comprehensive approach to the selection and control of starter cultures is a prerequisite for ensuring the biological safety of fermented meat products for consumers.

The starter culture market in the meat-processing industry. The production of starter cultures is a complex, science-driven process involving specialists from various scientific disciplines. However, growing consumer demand for fermented meat products is driving the expansion of the starter culture market [16], a trend that exhibits distinct geographical and economic features.

From a geographical perspective, the market exhibits a clearly defined regional structure. Western and Southern Europe (particularly Italy, Spain, France, and Germany) are the primary users of starter cultures, owing to a centuries-old tradition of producing air-dried and cold-smoked meat products. The North American region consistently employs bacterial cultures as protective agents for ensuring process safety and quality assurance in meat production technologies. Concurrently, the Asia-Pacific region, in which China and South Korea play a key role, is characterized by the fastest adoption of biotechnological solutions, driven by the rapid modernization of the regional food industry. The economic characteristics of this market are defined by significant barriers to switching suppliers of starter cultures among manufacturers. In this context, any substitution of starter culture at an industrial facility carries the risk of production failure, changes in the sensory profile of the finished product, and the need for revalidation of production lines. This ensures a high level of customer loyalty for the world's leading starter culture manufacturers [128, 129].

Commercial starter cultures for the meat industry are available in two main forms: freeze-dried and frozen cultures [128, 129].

The global leader in the biotechnology industry is Novonesis (Denmark), which was established in 2024 through the merger of Novozymes and Chr. Hansen [130]. Other tier-one manufacturers include IFF/Danisco (U.S./France), NovaTaste (Austria/Germany), DSM-Firmenich (Netherlands/Switzerland), SACCO System (Italy), and Lallemand Inc. (Canada/France). More specialized and regional manufacturers include Meat Cracks (Germany), Biochem (Italy), Almi (Austria), BioSource (U.S.), Kerry (Ireland), LB Bulgaricum, Lactina (Bulgaria), Dalton Biotecnologie (Italy), Angel Yeast (China), and BIFIDO Co. Ltd. (South Korea).

In response to the growing demand for vegan products, starter culture manufacturers are developing advanced fermentation systems designed to reduce beany off-flavours, achieve a natural colour profile, and replicate meat-like texture and umami flavour in meat alternatives. Key players in this segment include Novonesis, IFF/Danisco, and DSM-Firmenich.

Increasing safety requirements for fermented meat products and the need for standardized product quality are driving domestic demand for high-quality starter cultures. The starter culture market in Ukraine is growing despite several ongoing challenges. The primary impact is associated with martial law, which complicates logistics, disrupts contract execution, and reduces industrial production volumes of fermented meat products. The second key factor is exchange rate risk, which affects the cost of imported products. Despite these challenges, leading distributors are maintaining stable supply chains, while industrial companies are accumulating strategic reserves. There is no domestic production of this product segment in Ukraine, and the market is entirely dependent on imports. Table 1 lists the leading producers of meat starter cultures available on the Ukrainian market.

Table 1 – Distributors of starter cultures for the meat industry

Starter culture distributors	Company (manufacturer)	Products	Applications in meat processing
LLC «Lactol»	Novonesis (Denmark)	BACTOFLAVOR® BACTOFERM® SAFEPRO®	Salami, pepperoni, chorizo
		BACTOFERM® C-P-77 BACTOFERM® SM-75	Dry-cured meat products (ham, prosciutto)
		SAFEPRO® ImPorous SAFEPRO® B-LC-78 SAFEPRO® B-LC-48	Bacon
		SAFEPRO® B-LC-48 BACTOFERM® CS-300	Sausages and frankfurters
		SAFEPRO® B-LC-48 SAFEPRO® ImPorous BACTOFERM® CS-300 BACTOFERM® Rubis	Cooked meat and poultry products
		SAFEPRO® B-SF-77	Raw fermented meat products and meat semi-finished products
		Culture series: Bactoferm® SafePro®	Semi-finished and RTE meat products
LLC «Danisco Ukraine»	IFF/Danisco (USA/France)	Texel® SA-301 SPP-581 NEO1	Dry-cured and fermented sausages
Representative office DSM-Firmenich Ukraine	DSM-Firmenich (Netherlands/Switzerland)	Delvo®Guard	Raw fermented sausages and meat semi-finished products
		CombiSafe	RTE meat products
Kerry Group representative office Ukraine	Kerry (Ireland)	Bio-Preservation	Dry-cured and smoked fermented meat products
NovaTaste Ukraine LLC	NovaTaste (Austria/Germany)	BITEC® STARTER LD 20 BITEC® STARTER LS 25	Salami, dry-cured and cooked sausages
		BITEC® STARTER RP 3	Whole-muscle delicacies
		B-Range	RTE products and semi-finished products
		BITEC COTTO	Cooked sausages and hams
		BITEC B FRESH	Fresh meat and minced meat
Almi Ukraine	Almi (Austria)	Almi 7	Salami, dry-cured and semi-dry sausages
		Almi 2	Dry-cured meat products
Moguntia Ukraine	MOGUNTIA FOOD GROUP (Austria))	PokelSTART	Whole-muscle products, steaks
		PrestoSTART	Smoked and dry-cured sausages
		RedSTART	Fermented sausages

Most of the multinational companies and brands listed have a presence in the Ukrainian market. However, the nature of this presence varies considerably: some operate through direct subsidiaries or representative offices, while others function via a network of exclusive importers, large ingredient distributors, or through their B2B divisions.

Conclusion

An analysis of scientific publications indicates that starter cultures have a significant impact on technological processes in the production of fermented meat products. This is one of the most promising areas for increasing production efficiency and ensuring high-quality finished products. For the domestic meat processing industry, the scientifically grounded introduction of starter cultures is particularly important in the context of harmonizing domestic legislation with EU requirements regarding food safety, microbiological criteria, and the management of biological risks.

Evidence suggests that starter cultures containing both LAB and CNS are among the most effective for fermented meat production. The most effective combination is considered to be a combination of *Lactiplantibacillus plantarum*, *Lactilactobacillus sakei*, and *Pediococcus pentosaceus* in combination with *Staphylococcus carnosus* or *Staphylococcus xylosus*, as these mixtures promote enhanced acidification, colour stabilization, flavour development, and inhibition of undesirable microorganisms. Another key focus is the use of autochthonous starter cultures adapted to local raw materials and traditional processing methods for Ukrainian meat products.

A number of scientific and practical issues have also been identified that require further investigation. In particular, the use of autochthonous microflora from Ukrainian meat raw materials as a source of new starter cultures remains insufficiently studied. A limited number of studies have addressed the adaptation of European commercial starter cultures to local production conditions, the characteristics of local raw materials, and the technological parameters of Ukrainian enterprises. In addition, the development and use of environmentally safe packaging materials with high barrier properties remains insufficiently explored in global practice.

Therefore, promising areas of research for Ukrainian scientists include the selection of indigenous high-performing starter cultures; the development of multi-component microbial mixtures capable of ensuring the production of standardized products and reducing the use of synthetic preservatives; the selection of starter cultures with probiotic properties, enabling fermented meat products to be positioned as functional foods; the development and implementation of environmentally safe packaging materials; and the harmonization of safety assessment criteria for starter cultures in accordance with EU regulations and EFSA recommendations.

Overall, the use of modern starter cultures represents a strategic development area for the Ukrainian meat processing industry, contributing to increased competitiveness of domestic products, compliance with European safety and quality standards, and integration into the single European market.

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THE USE OF STARTER CULTURES IN THE TECHNOLOGY FERMENTED MEAT PRODUCTS

Агунова Л.В., кандидат технічних наук, доцент, *E-mail:* agunova.lora@gmail.com
Кафедра технології м'яса, риби і морепродуктів
Одеський національний технологічний університет
вул. Канатна, 112, м. Одеса, Україна, 65039

Анотація. У статті узагальнено наукові дані щодо біохімічних механізмів дії стартових культур у технології ферментованих м'ясопродуктів та їх впливу на безпечність, термін зберігання, харчову і біологічну цінність продукції. Використання стартових культур є ключовим інструментом керування ферментацією, забезпечення відтворюваності виробництва та безпечності готової продукції. Основні групи мікроорганізмів – молочнокислі бактерії, коагулазонегативні стафілококи, дріжджі та плісняві гриби – беруть участь у формуванні органолептичних властивостей, стабілізації кольору, розвитку аромату і структурних показників. Мікробіологічна безпечність забезпечується швидким зниженням pH, конкурентним витісненням небажаної мікрофлори, продукуванням органічних кислот і бактеріоцинів. Найефективнішими визнано комбіновані культури, що поєднують молочнокислі бактерії та коагулазонегативні стафілококи. Стартові культури подовжують термін зберігання завдяки багатобар'єрній системі захисту, що поєднує біоконсервацію із сучасними способами пакування. Мікробний протеоліз і ліполіз формують стабільні сенсорні характеристики, а також сприяють утворенню вільних амінокислот і біоактивних пептидів, підвищуючи засвоюваність білків. Вказано, що перспективним є використання пробіотичних штамів, здатних синтезувати γ-аміномасляну кислоту та інші біологічно активні сполуки. Водночас існують ризики: поширення антибіотикорезистентності, бактеріофагова контамінація, утворення біогенних амінів, наявність факторів вірулентності – що потребує геномного скринінгу перед використанням нових штамів при виробництві м'ясопродуктів. Перспективними напрямами є селекція автохтонних штамів, створення багатокомпонентних мікробних композицій, розроблення функціональних продуктів та впровадження екологічно безпечного пакування. Це визначено як стратегічний шлях підвищення конкурентоспроможності української м'ясопереробної галузі та її гармонізації з європейськими стандартами якості і безпечності.

Ключові слова: стартові культури, ферментовані м'ясопродукти, безпечність, відтворюваність, термін зберігання, харчова цінність

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