

Review Article

Preservation of Meat Products with Bacteriocins Produced by Lactic Acid Bacteria Isolated from Meat

Roger J. da Costa ¹, Flávia L. S. Voloski ¹, Rafael G. Mondadori ², Eduarda H. Duval,¹
and Ângela M. Fiorentini ¹

¹Post Graduate Program of Food Science and Technology, Faculty of Agronomy Eliseu Maciel, Federal University of Pelotas, Pelotas, RS 96010-900, Brazil

²Institute of Biology, Federal University of Pelotas, Pelotas, RS 96010-900, Brazil

Correspondence should be addressed to Ângela M. Fiorentini; angefiore@gmail.com

Received 11 October 2018; Revised 5 December 2018; Accepted 13 December 2018; Published 10 January 2019

Academic Editor: Giuseppe Zeppa

Copyright © 2019 Roger J. da Costa et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Bacteriocins are ribosomal-synthesized antimicrobial peptides that inhibit the growing of pathogenic and/or deteriorating bacteria. The most studied bacteriocin-producing microorganisms are lactic acid bacteria (LAB), as they have great potential application in food biopreservation, since the majority have GRAS (Generally Recognized as Safe) status. The LAB-producing bacteriocins and/or bacteriocins produced by these bacteria have been widely studied, with the emphasis on those derived from milk and dairy products. On the other hand, isolates from meat and meat products are less studied. The objective of this review is to address the main characteristics, classification, and mechanism of action of bacteriocins and their use in food, to highlight studies on the isolation of LAB with bacteriocinogenic potential from meat and meat products and also to characterize, purify, and apply these bacteriocins in meat products. In summary, most of the microorganisms studied are *Lactococcus*, *Enterococcus*, *Pediococcus*, and *Lactobacillus*, which produce bacteriocins such as nisin, enterocin, pediocin, pentocin, and sakacin, many with the potential for use in food biopreservation.

1. Introduction

Consumers are increasingly concerned about the effects of food intake in their health. These effects are related with allergies, behavioral changes, and carcinogenic effects, leading to the option for fresh and natural foods, processed with little or even without synthetic additives [1]. In addition, the possible contamination of fresh meat and meat products, together with the ability of some microorganisms to adapt easily to unfavorable environmental conditions, may represent a microbiological risk [2], while *Listeria monocytogenes* can survive to dry sausage processing despite several obstacles, such as low pH, salt, and nitrites, and can cause food-borne diseases (FBD) [3, 4].

Biopreservation is an important approach to maintain the microbiological quality and safety of meat and meat products. This technique is used to extend food shelf-life

through the application of a protective microbiota, for example, the use of lactic acid bacteria (LAB) with their antibacterial properties, such as the production of bacteriocins [5]. Bacteriocins are small peptides or bioactive proteins, ribosomally synthesized by Gram-positive and Gram-negative bacteria, and extracellularly released. These molecules have antimicrobial activity against pathogenic and deteriorating bacteria, justifying their biotechnological potential [6, 7]. Besides extending the shelf-life, bacteriocins also reduce the risk of transmission of pathogenic microorganisms, permitting the reduction in the use of synthetic preservatives [8, 9].

The antimicrobial potential of bacteriocins has allowed the development of LAB that produces them [10]. By 2015, around 185 LAB-producing bacteriocins were isolated and only 53% were well characterized and molecularly sequenced [11]. This group of microorganisms is considered safe for

consumption, has a long tradition as food-grade bacteria, and may exert a bioprotective or inhibitory effect against other microorganisms as a result of competition for nutrients and/or the production of bacteriocins or other antagonistic compounds such as organic acids, hydrogen peroxide, and enzymes [8]. Among the LAB found in meat and meat products, *Lactobacillus sakei* and *Lactobacillus curvatus* have been described as the main producers of these antimicrobial compounds, being responsible for the production of sakacins and curvacins, respectively [2, 3, 12, 13].

The objective of this review was to discuss the main characteristics, classification, and mechanism of action of bacteriocins produced by LAB isolated from meat and their use in food. The review will also discuss about the studies that characterized, purified, and/or used bacteriocins in meat products.

2. General Aspects of Bacteriocins

Bacteriocins are antimicrobial peptides, which act against Gram-positive and Gram-negative bacteria, but the producing bacteria carry specific immune mechanisms that protect it from its own bacteriocin [14, 15]. They are widely recognized as safe, nonactive, or cytotoxic substances to eukaryotic cells, inactivated by digestive enzymes (proteases), with little influence on the intestinal microbiota. They have bactericidal and/or bacteriostatic activity, usually targeting bacteria cytoplasmic membrane. Moreover, they do not express antibiotic resistance and their genetic determinants are encoded in plasmids, facilitating the genetic manipulation [9].

The bacteriocins produced by LAB are distinguished by their biochemical, genetic, structural, and metabolic activity. Most have reduced molecular weight (from 3 to 10 kDa), are electrically neutral, and have hydrophilic and hydrophobic regions [16]. Currently, there are controversies regarding the classification of bacteriocins, but despite this, one of the most recent classifications [15] separated the bacteriocins produced by Gram-positive and Gram-negative bacteria.

2.1. Classification of Bacteriocins. Bacteriocins produced by Gram-positive bacteria were divided into classes I and II. Class I bacteriocin, such as nisin, have low molecular weight (<10 kDa) and are thermostable, hydrophobic, and cationic peptides with modified posttranslational residues such as lanthionine and methylanthionine. Nisin acts by triggering the formation of pores, leading to dissipation of the membrane potential and efflux of small metabolites into sensitive cells [17, 18]. Class II bacteriocins are also of thermostable, hydrophobic, cationic, and low molecular weight (<10 kDa) peptides but generally have an amphiphilic helical structure, allowing their insertion into the cytoplasmic membrane of the target cell, promoting membrane depolarization and cell death [19]. Former Class III bacteriocins were excluded and in the previous classification were related to peptides with high molecular weight (>30 kDa) and heat-labile. Class III bacteriocins were subdivided into subclasses IIIa or bacteriolysins and

IIIb. Former subclass IIIa peptides (lysostaphin and enterolysin A) promote cell lysis by hydrolysis of the cell wall. In contrast, previous subclass IIIb (helveticin J) comprises peptides that did not cause lysis but dissipation of membrane potential and reduction in intracellular concentration of ATP. On the other hand, former Class IV molecules (bacteriocins complexes, as lactocin 27 and leuconocin S, usually globular, with activity dependent on the association of one or more functional groups such as carbohydrates or phospholipids) are not considered bacteriocins anymore, since the designation of bacteriocins would correspond only to small peptides synthesized in ribosomes, not including other high molecular weight antimicrobial proteins [20–22].

Class II bacteriocins are divided into subclass IIa, IIb, and IIc. Some bacteriocins from subclass IIa, the largest subclass with more than 50 members described, are pediocin PA-1, sakacin A and P, enterocin A and P, leucocin A, curvacin A, and carnobacteriocin B2 [23]. Besides their restricted spectrum of inhibition, these molecules are known for the strong anti-listerial activity, and its genetics, structure, and mechanism of action have been extensively studied [18]. In addition, they may have activity spectrum against other deteriorating and pathogenic microorganisms such as *Brochothrix* spp., *Clostridium* spp., *Bacillus* spp., and *Staphylococcus* spp. [24]. The subclass IIb comprises heterodimeric bacteriocins that require the combined activity of two peptides. Its mechanism of action involves dissipation of the membrane potential and decreasing of intracellular ATP concentration. The first reported bacteriocin, containing two peptides and obtained from a meat LAB, was lactocin 705 produced by *Lactobacillus curvatus* CRL705. This molecule has inhibitory activity against some LAB and also against *Brochothrix thermosphacta* [25, 26]. In addition, plantaricin EF, JK, and S (*Lactobacillus plantarum*), enterocin 1071 (*Enterococcus faecalis*), lactococcin G and MN (*Lactococcus lactis*) [22], and more recently lactococcin Q (*Lactococcus lactis* QU 4 from corn) and enterocin X (*Enterococcus faecium* KU-B5 from Thai sweet apple) [11, 27] also belong to the same subclass. Finally, subclass IIc bacteriocins (formerly Class V) have a covalent union of the carbon (C) and nitrogen (N) terminations, resulting in a cyclic structure. Circularin A (*Clostridium beijerinckii*) and reuterin 6 (*Lactobacillus reuteri*) [22] and those produced by LAB isolated from meat such as enterocin AS-48 (*Enterococcus* from various meat products), carnocycline A (*Carnobacterium maltaromaticum* UAL307 from pork meat), and garvicin ML (*Lactococcus garvieae* DCC43 from poultry meat) [28] are some examples of molecules from subclass IIc.

According to this classification, Class I corresponds to bacteriocins that undergo extensive posttranslational modifications. Class II, however, includes bacteriocins that do not undergo such modifications and also those that undergo other simple modifications such as the formation of disulfide bridges or their circularization. The bacteriocins produced by Gram-negative bacteria belong to two distinct groups, one of small peptides, such as microcins (*Escherichia coli*), and a second of large peptides, colicins (*Escherichia coli*) [20, 22].

2.2. Synthesis and Mechanism of Action. The mechanism of bacteriocins' synthesis can often be induced by stress conditions such as population increase and nutrient shortage, as well as can be affected by the type of carbon, nitrogen, and phosphate sources present in the media, or even by cation surfactants and other inhibitors [29, 30]. In addition, it can also be regulated by quorum sensing, that is, a cell-to-cell communication where they produce self-induced molecules as a result of population density [16, 31]. The threshold that activates the production of bacteriocins varies among microorganisms and is based on the synthesis of peptides called pheromones, which after reaching this threshold activate the production of bacteriocins [16, 32, 33].

The production of bacteriocins occurs during, or at the end, of the exponential growth phase, maintaining a direct relation with the production of biomass, and by the regulation of inducer peptides (pheromones). This pheromone is synthesized in the ribosome and secreted in the outer environment by the carrier system. When this compound reaches a threshold concentration, which depends on transcriptional activity in the producing cell, as well as on the number of cells present, it activates transmembrane histidine kinase, which leads to autophosphorylation of the histidine residue, thus transferring phosphate to a response regulator protein. The phosphorylated regulator activates the transcription of the bacteriocin by the expression of four genes: the first one is responsible for the production of the biologically inactive prepeptide; the second allows the production of a specific immunity protein to the producer cell; the third is the gene encoding proteins from the ABC transporter responsible for exteriorizing the bacteriocin; and finally, the fourth gene encodes an essential accessory protein for bacteriocin exteriorization [16, 32–34]. After undergoing modifications, premature prepeptides are enzymatically cleaved to remove the signal sequence and are transported to the extracellular medium, as a mature bacteriocin [16, 31, 35].

There is a consensus regarding the hypothesis that most bacteriocins interact with cell membrane anionic lipids of the target bacteria, causing their permeabilization through the formation of pores. Eventually, this interaction can cause the death of the target cell, promoting the dissipation of the proton motive force (PMF) and the inhibition of amino acids transport. PMF is involved in several processes in the cell membrane, such as the accumulation of ions and metabolites, and ATP synthesis [36, 37].

The two possible mechanisms of action of bacteriocins in Gram-positive bacteria are shown in Figure 1 [15]. In Class I model, bacteriocins cross the cell wall, inhibiting lipid II in the cell membrane, preventing the synthesis of peptidoglycan (cell wall component). In the Class II model, there is also the passage through the cell wall and the formation of pores in the cell membrane, through the connection to a pore-forming receptor in the mannose-phosphotransferase system. In addition, it is also known that some Class I bacteriocins, such as nisin, can act via both mechanisms of action.

The sensitivity of Gram-positive and Gram-negative bacteria to bacteriocins is based on the chemical

composition of the cell wall. To allow the bacteriocin bactericidal effect, the indicator microorganism should have antimicrobial susceptibility permitting, even at low bacteriocin concentrations, the rapid cell death. In addition, bacteriocins may also have bacteriostatic action, depending on dose, degree of purification, physiological state of the indicator cells (e.g., growth phase), and experimental conditions (temperature, pH, and presence of agents altering the cell wall integrity and other antimicrobial compounds) [38, 39].

Although many LAB-produced bacteriocins such as nisin and pediocin have been approved by the competent authorities and widely used in food products [36], the inability to inhibit Gram-negative pathogens, main causes of FBD, limits their applications [32, 40, 41]. Therefore, strategies for the use of bacteriocins against these microorganisms have been tested. In this sense, it has already been observed that destabilization of the cell wall outer membrane by chemical (organic acids, EDTA, essential oils, or chelating agents) or physical (pH, heating, freezing, high hydrostatic pressure, or pulsed electric field) stress increased the sensitivity of Gram-negative bacteria to bacteriocins, allowing that the molecule transverse the cell wall, reaching the cell membrane [15, 24, 42–45].

As not all bacteriocin characteristics are known [46], some peptides have shown an additional or synergistic effect when used in combination with other compounds or treatments, considering them as part of the obstacles theory (barrier mechanism) [47]. In this context, the use of sequential interventions at different processing points of meat and meat products (multiple obstacle theory) should be considered in order to improve the microbiological safety of beef, poultry, and their products [23].

3. Bacteriocins Production by LAB Isolated from Meat

During the past 10 years, numerous studies in different countries have been conducted to isolate LAB from meat and meat products and study their bacteriocinogenic potential for future application in food products. Some examples will be described in the following section.

Evaluating 30 samples of different meat products, such as ground beef, processed meat, viscera, poultry, bacon, pork, and fish, Gomes et al. [48] isolated 60 LAB, but only 9 showed bacteriocinogenic activity. Prevalence of *Enterococcus* sp. in the products was 60%, where *E. faecium* and *E. faecalis* were, respectively, the most commonly found species. Also, Dal Bello et al. [49] isolated LAB from 51 meat products (8 fresh and 43 fermented), with the predominance of *Lactococcus* and *Enterococcus*. From this, 23 isolates produced bacteriocin, with bacteriocinogenic potential against *L. monocytogenes*, *B. thermosphacta*, and *S. aureus*, by encoding the genes *nisA*, *nisZ*, *entA*, and *entP*.

In the research conducted by Castro et al. [50], analyzing different fermented sausages, 141 strains with LAB characteristic were isolated, and only one that showed sensitivity to trypsin and proteinase K was identified as *Lactobacillus curvatus/sakei* ACU-1. This bacteriocin exhibited thermal

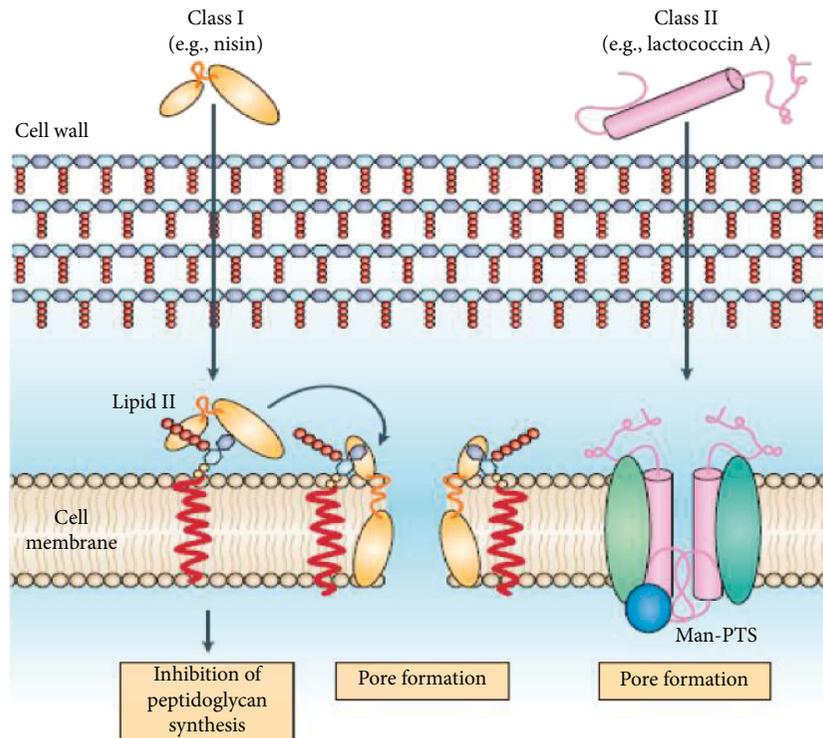


FIGURE 1: Mechanism of action of bacteriocins on Gram-positive bacteria [15].

stability over a wide range of time and temperature and also during storage under refrigeration and freezing conditions. Its production was directly influenced by the presence of surfactants and the concentration of NaCl and was not affected by the presence of KCl, EDTA, potassium sorbate, and sodium citrate. Rivas et al. [51], also working with *L. curvatus* ACU-1 isolated from fermented sausage, detected the structural gene *sppQ*, encoding the sakacin Q, a subclass IIC bacteriocin. The CFS (cell-free supernatant) was applied to the surface of meat previously inoculated with *L. innocua*, and the bacteriocin was able to inhibit growth of the indicator microorganism after 4 weeks of storage. Ali et al. [52] isolated 30 LAB from 7 beef samples, and only 2 isolates (*Lactobacillus curvatus* and *Lactobacillus graminis*) produced stable bacteriocins at temperatures ranging from 40 to 60°C and at pH 5 to 7.

Fontana et al. [3] isolated 115 LAB with anti-listeria activity from raw meat and fermented meat products from Argentina. The species obtained were *Lactobacillus sakei* (71 isolates), *Lactobacillus curvatus* (14 isolates), *Lactobacillus plantarum* (7 isolates), *Enterococcus faecium* (16 isolates), and *Pediococcus acidilactici* (7 isolates). The following genes were identified: *sapA* (curvacin A), *sppQ* (sakacin Q), *sppA* (sakacin P), *plnEF* (plantaricin EF), *plnA* (plantaricin A), *entA* (enterocin A), *entP* (enterocin P), and *entB* (enterocin B). The study determined the potential of *L. sakei* and *E. faecium* as bioprotective cultures and an additional obstacle in the control of *L. monocytogenes* in raw meat and meat products.

L. curvatus 54M16 isolated from traditional fermented sausages from Italy was able to produce more than one bacteriocin, since it had the coding genes for sakacin X, T,

and P. It presented antimicrobial activity especially against Gram-positive bacteria such as *L. monocytogenes*, *Bacillus cereus*, and *Brochotrix thermosphacta*, a major meat spoilage. In addition, the microorganism itself has shown good potential to be used as a starter culture in the production of fermented sausages, positively affecting the taste and general acceptability of the products [2].

Besides the promising results for their application as bioconservatives, Table 1 shows that, although LAB in meat and meat products are somewhat common, few studies evaluated their bacteriocinogenic activity, mainly when compared to those from milk products.

4. Use of Bacteriocins in Food

The meat industry uses preservatives such as curing salts (sodium or potassium nitrite and nitrate) to inhibit microbial growth, fix color, add characteristic flavor and aroma, and delay lipid oxidation. In fermented sausages (ready to eat), the addition of these chemical additives aims to inhibit the growth of *Clostridium botulinum*, whose toxin causes botulism [66, 67]. Besides the beneficial effects resulting from the use of these constituents, excess consumption could have harmful effects on human health, mainly by the formation of carcinogenic substances such as nitrosamines [67, 68].

Due to consumer demand for natural and good microbiological quality foods, as well as stringent government requirements, food manufacturers face conflicting challenges to ensure food safety [69]. Thus, with increasing negative perceptions of synthetic chemical additives, natural

TABLE 1: Characterization (temperature and pH stability, spectrum of action, surfactants, and additives) of LAB isolated from meat and meat products.

Microorganism producer/ bacteriocin	Source	Stability	Spectrum of action	Reference
<i>Pediococcus acidilactici</i> /Pediocin SA-1	Dry sausage	100°C/121°C/60 min −80, −20, 4, and 30°C pH 3–12	Pathogens Spoilages	[53]
<i>Lactobacillus plantarum</i> LP 31/ Plantaricin	Dry-fermented sausage	High temperature Low pH High and low temperatures pH 3–9	<i>S. aureus</i> / <i>L. monocytogenes</i> <i>B. cereus</i> / <i>Pseudomonas</i> sp. <i>E. coli</i> / <i>B. cereus</i> / <i>S. aureus</i> <i>Salmonella typhi</i> / <i>Vibrio cholerae</i> <i>Shigella</i> sp./ <i>E. faecalis</i>	[54]
<i>Pediococcus acidilactici</i>	Fresh meat	High and low temperatures pH 2.0–12.0		[55]
<i>Lactobacillus plantarum</i> / BacST202Ch BacST216Ch	Pork smoked sausage	Triton X-100/Tween 80/ Tween 20 SDS (sodium dodecyl sulfate) NaCl/urea/EDTA	Gram-positive Gram-negative	[56]
<i>Enterococcus faecium</i> NKR-5-3/ Enterocins NKR-5-3A, B, C, D, Z	Fermented fish	Temperature Salt	<i>Enterococcus</i> / <i>Lactobacillus</i> <i>Bacillus</i> / <i>Listeria</i>	[57]
<i>Enterococcus faecium</i> M3a/ Enterocin A, P, B	Rabbit meat	5% bile salts low pH	<i>L. monocytogenes</i> CCM 4699 <i>S. aureus</i> 3A3 <i>S. enterica</i> serovar enteritidis PT4	[58]
<i>Lactococcus lactis</i> subsp. <i>Lactis</i> 69/ Nisin Z	Beef jerky	High temperatures pH 2–10 SDS/EDTA/Tween 80/ urea 20% NaCl	Spoilages Halotolerant	[59]
<i>Lactobacillus sakei</i> ST22Ch ST153Ch ST154Ch	Fermented and cured pork sausage	Up to 100°C pH 4–10 Triton X-100/Tween 20/ Tween 80 SDS/NaCl/urea/EDTA	<i>E. faecium</i> ATCC 19443 <i>L. ivanovii</i> subsp. <i>ivanovii</i> ATCC 19119 <i>L. monocytogenes</i> NCTC 11944, NCTC 7973 and Scott A	[13]
<i>Lactobacillus plantarum</i> BM-1/ Plantaricin BM-1	Fermented meat product	High temperatures pH 2–10	Gram-positive Gram-negative	[60]
<i>Lactobacillus curvatus</i> MBSa2 and MBSa3/Sakacin P and X	Italian-type salami	Temperatures: 4–121°C pH 2–8 NaCl 2–10% High and low temperatures pH	<i>L. monocytogenes</i>	[12]
<i>Weissella hellenica</i> BCC 7239/ 7293A and 7293B	Fermented pork sausage	Ethanol/isopropanol/ acetone Acetonitrile/Tween 20/ Tween 80 Triton X-100 High and low temperatures Acid pH	Gram-positive Gram-negative: <i>P. aeruginosa</i> / <i>S. Typhimurium</i> <i>Aeromonas hydrophila</i> / <i>E. coli</i>	[61]
<i>Lactobacillus plantarum</i> M1- UVs300/M1-UVs300	Fermented sausage	Sodium citrate/sodium erythorbate Sodium tripolyphosphate	Gram-positive Gram-negative	[62]
<i>Lactobacillus plantarum</i> -GS16 <i>Lactobacillus paraplantarum</i> -GS54/ L.p.-GS16 L.p.p.-GS54	Sliced ham	100°C/60 min Refrigeration (2 months) pH 2–10	Gram-positive Gram-negative	[63]

TABLE 1: Continued.

Microorganism producer/ bacteriocin	Source	Stability	Spectrum of action	Reference
<i>Lactobacillus alimentarius</i> FM-MM ₄ / Lactocine MM ₄	Fermented meat product	High and low temperatures pH 2–5	Gram-positive Gram-negative Yeasts: <i>Saccharomyces cerevisiae</i> <i>Pichia</i> sp./ <i>Candida albicans</i> <i>P. fluorescens</i> / <i>P. aeruginosa</i> <i>Vibrio harveyi</i> / <i>B.cereus</i>	[64]
<i>Lactobacillus plantarum</i> DY4-2/ DY4-2	Fish	50°C, 100°C, and 121°C/ 30 min pH 2.5–5.5	<i>Shewanella putrefaciens</i> <i>Psychrobacter</i> sp./ <i>B. licheniformis</i> <i>L. monocytogenes</i>	[65]

antimicrobial agents, such as bacteriocins, have been extensively studied and tested for their efficacy [11].

The use of bacteriocins in biopreservation systems can meet consumers' demand for natural preservatives and is also considered an additional safety measure to minimally processed products, which depend only on refrigeration as a conservation medium [70]. Furthermore, since bacteriocins are able to kill the target microorganism by disrupting membrane integrity, they are less likely to induce resistance, since their fragments do not interact with target cells, and can be considered a potential solution for the growing problem of microbial resistance to antibiotics [15, 71, 72].

According to Ross et al. [73], the potential for application of a given bacteriocin can be predicted by its properties, such as temperature stability, pH, and broad action spectrum. In addition, the use of bacteriocins may not pose risks to the consumer's health or affect the nutritional and sensory quality of the food, and the producing bacteria should have GRAS status [44].

In general, there are three ways in which bacteriocins can be incorporated into a food to enhance their safety: (1) using a purified or semipurified preparation of bacteriocin as a food ingredient; (2) by the incorporation of an ingredient that has previously been produced by a bacteriocin-producing LAB; or (3) by the use of bacteriocin-producing LAB as the starter or adjunct culture directly in the fermented product for the *in situ* production of bacteriocin [14, 47, 74].

The available literature describes the use of different strategies for the application of bacteriocins in food: (1) direct addition in food formula or immersion in a solution containing the peptide; (2) adsorption of bacteriocin in polyethylene-type plastic films, cellulose edible films, and on surfaces such as ethylene vinyl acetate, polypropylene, polyester, and others; (3) and antimicrobial coatings containing bacteriocin preparations and LAB cultures. All these techniques can be used as technological strategies based on the theory of multiple obstacles, aiming to reduce FBD [19, 40, 44, 75, 76].

According to Castellano et al. [23], to ensure the effectiveness of its activity, tests against specific target bacteria must be performed on the food in which the bacteriocin will be applied. Thus, some factors may influence the propagation of bacteriocins in the food, such as salt concentration, pH, nitrite and nitrate, enzymes, solubility, lipid content

and surface available for solubilization, uniform distribution in the food, and possible inactivation by other additives [77].

Nisin, a bacteriocin produced by *Lactococcus lactis* subsp. *lactis*, is already being commercially used in some countries. This bacteriocin was first described by Rogers [78] as a substance inhibiting the growth of *Lactobacillus bulgaricus* [79]. Nisin also inhibits the growth of other Gram-positive and *Clostridium* and *Bacillus* spores [80] and was recognized as a food additive by FAO/WHO in 1969, with the maximum limit for ingestion of 33,000 international units/kg (IU/Kg) of body weight. More than 50 countries allow their use in products such as milk, processed cheese, grated cheese, dairy products, tomatoes and other canned vegetables, soups, and meat, as well as brewery products and mayonnaise [70, 73, 81]. Another bacteriocin that can be used as a commercial ingredient in the biopreservation of foods such as dried sausages and fermented meat products is pediocin PA-1/AcH (ALTA™ 2341), produced by *Pediococcus acidilactici* [9, 22, 47].

4.1. Use of Bacteriocins in Meat and Meat Products.

Bacteriocins produced by LAB have been efficiently used in bovine and poultry carcasses and fresh meat. Spraying the products with a combination of nisin and lactic acid (1.5%, 25°C) was more efficient in reducing the count of aerobic bacteria, coliform, and *Escherichia coli* than the use of bacteriocin alone [82]. Furthermore, the use of bioprotective cultures of *E. faecium* PCD71, *Lactobacillus fermentum* ACA-DC179, and the combined application of different subclass IIa bacteriocins was able to reduce the growth of *L. monocytogenes* in different meat products [83–85]. However, the use of *L. plantarum* BFE5092, producer of plantaricin EF, JK, and N, in turkey meat stored under aerobic conditions at 10°C, failed to effectively inhibit *L. monocytogenes* [86].

The main limitations to the use of nisin in meat products are related to the low solubility of this bacteriocin in these products, the possibility of enzymatic destruction, and the inefficiency of inhibition of several important pathogenic or spoilage microorganisms [70]. Considering this, after nisin, the pediocin (*Pediococcus acidilactici*) is the most studied bacteriocin due to its antimicrobial activity against *Listeria* spp. Its action is empirically related to the use of this strain as a starter culture in a number of fermented foods [87], such

as vegetables (sauerkraut), meat (sausages) [88], and dairy products (cheeses) [19]. In meat industry, pediocin PA-1 or this bacteriocin-producing culture reduces the growth of spoilage microorganisms during storage. Moreover, its use can be combined with other conservation technologies, since it has the advantage of being active at low pH and acts synergistically with other compounds such as lactate or organic acids [19].

Various papers related the efficiency of pediocin in meat products. Pediocin and nisin were able to reduce the counts of *Lactobacillus sakei* in samples of vacuum-packed sliced ham [89]. *P. acidilactici* MCH14, pediocin PA-1 producer, also inhibited *L. monocytogenes* and *Clostridium perfringens* in dry fermented sausage produced in Spain [90]. In addition, strain *P. pentosaceus* BCC3772 (pediocin PA-1/AcH producer) was able to exert anti-listerial activity during the fermentation of a traditional Thai pork sausage without significantly altering its sensorial characteristics [91].

In the next section, we will describe the use and effect of some bacteriocins on different meat products. Pentocin 31-1, produced by *Lactobacillus pentosus* 31-1 (isolated from a traditional Chinese fermented ham), increased the shelf life of packaged refrigerated pork in 15 days, maintaining its sensorial and physicochemical characteristics; in addition, it inhibited the growth of pathogens, such as *L. monocytogenes*, and spoilage microorganisms, such as *Pseudomonas fluorescens* [92]. The semipurified bacteriocin BacTN635, produced by *Lactobacillus plantarum* sp. TN635, isolated from meat, inhibited the proliferation of spoilage microorganisms and *L. monocytogenes* in beef and chicken breast, increasing the shelf life of the refrigerated products. The bacteriocin also improved sensory quality (odor, texture, color, and overall acceptance) and texture attributes (hardness, elasticity, and stiffness) [93].

Another semipurified bacteriocin, BacFL31, produced by *Enterococcus faecium* sp. FL 31 obtained from meat product, also had an effect on sensory parameters and conservation of refrigerated ground turkey meat. The bacteriocin inhibited the proliferation of several spoilage microorganisms, avoiding oxidative rancidity and also inhibiting the pathogens *Listeria monocytogenes* and *Salmonella* Typhimurium, and maintained the pH at low levels. In addition, sensory parameters (odor, color, texture, and overall acceptance) were kept at acceptable levels for a longer time, increasing the shelf life [94]. *L. monocytogenes* counting in fermented sausage after 21 days of storage was also reduced by the use of the semipurified bacteriocin produced by *Leuconostoc mesenteroides* ssp. *mesenteroides* IMAU: 10231, isolated from this same product. This result is also technologically important, since the bacteriocin-producing strain is heterofermentative (produces CO₂ during fermentation), rendering ineffective its use by possibility of product stuffing; therefore, the bacteriocin should be used itself [95].

In contrast, homofermentative LAB (produces lactic acid instead of CO₂) could be used as a starter culture with technological and preservative purposes. As an example of this category, we could cite *Weissella paramesenteroides* DX, a homofermentative LAB isolated from fermented meat,

producer of weissellin A bacteriocin. Under aerobic conditions, this peptide was only produced in the absence or at low concentrations of the preservative sodium nitrite (NaNO₂). However, under anaerobic conditions (micro-environment found in fermented meat sausage), no inhibitory effect of NaNO₂ was observed, allowing the use of this microorganism in the biopreservation of this type of product [96].

As previously described, some ingredients used in meat products may influence the effective action of the bacteriocins. But some molecules, as the semipurified bacteriocin of *L. curvatus* MBSa2, reduced the contamination of *L. monocytogenes* in salami, without the interference of ingredients and additives, increasing the microbiological safety of this product [12]. In some cases, the direct application of CFS on meat matrix (pork and pork fat) may reduce the antimicrobial activity of bacteriocin [51]. To avoid this reduction, an alternative would be to apply bacteriocin as an active packaging component, thus reducing its direct contact with the food matrix. In this sense, several studies have used the incorporation of bacteriocins in packages to control pathogenic bacteria through the gradual release of the peptide in the food to avoid the possible inactivation of bacteriocin through interaction with the food components [97]. The use of films incorporated with antimicrobial substances have advantages over the conventional methods of direct addition of preservatives in foods, such as the use of a smaller amount of these substances and its controlled release, since they mainly act on the surface of the product [98].

Nisin is being widely used by this approach [99], reducing the contamination in three or more log cycles [100], while studies in liquid media have found reductions between six and nine log cycles, using nisin and chitosan as coating [101]. Nisin combined with polyethylene (PE), low-density polyethylene (LDPE), cellophane, chitosan, and isolated soy protein/essential oils has been shown efficient in the reduction of *L. monocytogenes*, *B. thermosphacta*, *Enterobacteriaceae*, and spoilage LAB in raw meat, sliced ham, and ground beef [102–105]. Pediocin incorporated in cellulose-based packages was also efficient in the inhibition of *L. monocytogenes* in sliced ham, turkey, and beef [106, 107]. Finally, enterocins added to an alginate, zein, and polyvinyl alcohol-based biodegradable film increased the safety of sliced ham, delaying or reducing the growth of *L. monocytogenes* [108].

Another alternative for the use of bacteriocins in meat products is through the application of bacteriocinogenic LAB strains with probiotic activity, which can reduce the pathogen count in the food or alter the composition of the intestinal microbiota in animals [71]. A probiotic microorganism must have GRAS status, survive the gastrointestinal transit to exert its beneficial effects by colonizing the intestinal mucus, tolerate the stomach pepsin and pH, and resist to the duodenum protease and bile salts. In addition, it should be able to adhere to the intestinal mucosa, which is a prerequisite for exerting its beneficial effects, such as the exclusion of enteropathogenic bacteria and the immunomodulation of the host [109]. With the growing interest for the possible probiotic's health promoting effects, the incorporation of LAB-producing bacteriocins with probiotic

potential is an excellent alternative, since besides guaranteeing food safety, they can also aid in the development of meat products with health benefits. However, additional studies are needed to determine the real benefits of probiotic bacteria in health promotion, both *in vitro* and *in vivo*, as well as to confirm the bacteriocin production and their safe levels of consumption [110]. For example, Swetwathana et al. [111] showed that a *P. pentosaceus* strain (pediocin-producing probiotic), when used as a starter culture in a fermented meat sausage, inhibited the growth of *Salmonella* Anatum.

As a bacteriocin mix would be considered more efficient, cells resistant to one bacteriocin would be inactivated by the other; therefore, the use of these mixtures would allow a better standardization of bacteriocinogenic activity. Bacteriocin extracts produced by LAB can be applied as a bioconservative meat products, including the ready to eat, and may act against pathogenic and/or spoilage microorganisms [112]. Based on this principle, Dortu et al. [84] evaluated the individual and combined effect of sakacin G and sakacin P, respectively, produced by *Lactobacillus sakei* CWBI-B1365 and *Lactobacillus curvatus* CWBI-B28, in the growth and survival of *L. monocytogenes* on beef and chicken meat. The respective microorganisms were isolated from these same raw materials and were applied to the surfaces of previously contaminated meat. These two bacteria were synergistically efficient on the inhibition of *L. monocytogenes*, especially in beef.

5. Final Considerations

This review shows the diversity of meat-derived LAB and meat product-derived LAB with bacteriocinogenic activity, mainly belonging to *Lactococcus*, *Enterococcus*, *Pediococcus*, and *Lactobacillus* genera. They produce bacteriocins such as nisin, pediocin, sakacin, pentocin, and enterocin, acting against pathogenic and/or spoilage microorganisms. Most of the bacteriocins obtained were stable at different temperatures, pH, salts, surfactants, and chemical additives. Thus, they become a future alternative in food biopreservation, since the application of bacteriocins in meat and meat products can help reduce the use of synthetic preservatives and/or the intensity of physical treatments, satisfying consumers' demands for fresh, healthy, and safe food.

This review has compiled important results on the characterization of bacteriocins produced by LAB isolated from meat and meat products and their use. The results discussed show the need for studies to evaluate the toxicity and the effect of these products in the food matrix. In addition, due to the reported strengths, other studies with pathogenic and spoilage microorganisms must be carried out in order to guarantee the safety and quality of meat product. Finally, it is evident that the wide possibility of application of bacteriocins should not be seen as a single solution, but as a good alternative in terms of food safety, especially when combined with other techniques.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

References

- [1] E. M. Balciunas, F. A. Castillo Martinez, S. D. Todorov, B. D. G. d. M. Franco, A. Converti, and R. P. d. S. Oliveira, "Novel biotechnological applications of bacteriocins: a review," *Food Control*, vol. 32, no. 1, pp. 134–142, 2013.
- [2] A. Casaburi, V. D. I. Martino, P. Ferranti, L. Picariello, and F. Villani, "Technological properties and bacteriocins production by *Lactobacillus curvatus* 54M16 and its use as starter culture for fermented sausage manufacture," *Food Control*, vol. 59, pp. 31–45, 2016.
- [3] C. Fontana, P. S. Cocconcelli, G. Vignolo, and L. Saavedra, "Occurrence of antilisterial structural bacteriocins genes in meat borne lactic acid bacteria," *Food Control*, vol. 47, pp. 53–59, 2015.
- [4] B. Martin, M. Garriga, and T. Aymerich, "Prevalence of *Salmonella* spp. and *Listeria monocytogenes* at small-scale Spanish factories producing traditional fermented sausages," *Journal of Food Protection*, vol. 74, no. 5, pp. 812–815, 2011.
- [5] C. P. Oliveira, J. P. S. Júnior, and J. A. Silva, "Bacteriocinas como alternativa na conservação de alimentos," *Revista verde de agroecologia e desenvolvimento sustentável*, vol. 7, no. 1, pp. 09–15, 2012.
- [6] F. A. C. Martinez, E. M. Balciunas, J. M. Salgado et al., "Lactic acid properties, applications and production: a review," *Trends in Food Science and Technology*, vol. 30, no. 1, pp. 70–83, 2013.
- [7] D. Beshkova and G. Frengova, "Bacteriocins from lactic acid bacteria: microorganisms of potential biotechnological importance for the dairy industry," *Engineering in Life Sciences*, vol. 12, no. 4, pp. 419–432, 2012.
- [8] P. Castellano, C. Belfiore, S. Fadda, and G. M. Vignolo, "A review of bacteriocinogenic lactic acid bacteria used as bioprotective cultures in fresh meat produced in Argentina," *Meat Science*, vol. 79, no. 3, pp. 483–499, 2008.
- [9] A. Gálvez, H. Abriouel, R. L. López, and N. B. Omar, "Bacteriocin-based strategies for food biopreservation," *International Journal of Food Microbiology*, vol. 120, no. 1–2, pp. 51–70, 2007.
- [10] A. J. van Heel, M. Montalban-Lopez, and O. P. Kuipers, "Evaluating the feasibility of lantibiotics as an alternative therapy against bacterial infections in humans," *Expert Opinion on Drug Metabolism and Toxicology*, vol. 7, no. 6, pp. 675–680, 2011.
- [11] W. Woraprayote, Y. Malila, S. Sorapukdee, A. Swetwathana, S. Benjakul, and W. Visessanguan, "Bacteriocins from lactic acid bacteria and their applications in meat and meat products," *Meat Science*, vol. 120, pp. 118–132, 2016.
- [12] M. S. Barbosa, S. D. Todorov, I. Ivanova et al., "Improving safety of salami by application of bacteriocins produced by an autochthonous *Lactobacillus curvatus* isolate," *Food Microbiology*, vol. 46, pp. 254–262, 2015.
- [13] S. D. Todorov, M. Vaz-Velho, B. D. G. de Melo Franco, and W. H. Holzapfel, "Partial characterization of bacteriocins produced by three strains of *Lactobacillus sakei*, isolated from *salpicão*, a fermented meat product from North-West of Portugal," *Food Control*, vol. 30, no. 1, pp. 111–121, 2013.
- [14] H. C. And and D. G. Hoover, "Bacteriocins and their food applications," *Comprehensive Reviews in Food Science and Food Safety*, vol. 2, no. 3, pp. 82–100, 2003.
- [15] P. D. Cotter, R. P. Ross, and C. Hill, "Bacteriocins—a viable alternative to antibiotics?," *Nature Reviews Microbiology*, vol. 11, no. 2, pp. 95–105, 2012.

- [16] V. G. H. Eijsink, L. Axelsson, D. B. Diep, L. S. Håvarstein, H. Holo, and I. F. Nes, "Production of class II bacteriocins by lactic acid bacteria; an example of biological warfare and communication," *Antonie van Leeuwenhoek*, vol. 81, no. 1–4, pp. 639–654, 2002.
- [17] B. H. F. N. S. S. I. M., and A. J., "Combinations of nisin with salt (NaCl) to control *Listeria monocytogenes* on sheep natural sausage casings stored at 6°C," *African Journal of Biotechnology*, vol. 9, no. 8, pp. 1190–1195, 2010.
- [18] P. Alvarez-Sieiro, M. Montalbán-López, D. Mu, and O. P. Kuipers, "Bacteriocins of lactic acid bacteria: extending the family," *Applied Microbiology and Biotechnology*, vol. 100, no. 7, pp. 2939–2951, 2016.
- [19] D. Drider, G. Fimland, Y. Hechard, L. M. McMullen, and H. Prevost, "The continuing story of class IIa bacteriocins," *Microbiology and Molecular Biology Reviews*, vol. 70, no. 2, pp. 564–582, 2006.
- [20] M. B. Ogaki, M. C. Furlaneto, and L. F. Maia Revisão, "Revisão: aspectos gerais das bacteriocinas," *Brazilian Journal of Food Technology*, vol. 18, no. 4, pp. 267–276, 2015.
- [21] N. C. K. Heng, P. A. Wescombe, J. P. Burton, R. W. Jack, and J. R. Tagg, "The diversity of bacteriocins produced by Gram-positive bacteria," in *Evolution and ecology of bacteriocins*, M. A. Riley and M. Chavan, Eds., pp. 45–92, Springer Inc., New York, NY, USA, 2007.
- [22] P. D. Cotter, C. Hill, and R. P. Ross, "Bacteriocins: developing innate immunity for food," *Nature Reviews Microbiology*, vol. 3, no. 10, pp. 777–788, 2005.
- [23] P. Castellano, M. Pérez Ibarreche, M. Blanco Massani, C. Fontana, and G. Vignolo, "Strategies for pathogen bio-control using lactic acid bacteria and their metabolites: a focus on meat ecosystems and industrial environments," *Microorganisms*, vol. 5, no. 3, pp. 38–63, 2017.
- [24] S. Ennahar, T. Sashihara, K. Sonomoto, and A. Ishizaki, "Class IIa bacteriocins: biosynthesis, structure and activity," *FEMS Microbiology Reviews*, vol. 24, no. 1, 2000.
- [25] P. Castellano, R. Raya, and G. M. Vignolo, "Mode of action of lactocin 705, a two-component bacteriocin from *Lactobacillus casei* CRL705," *International Journal of Food Microbiology*, vol. 85, no. 1–2, pp. 35–43, 2003.
- [26] P. Castellano and G. Vignolo, "Inhibition of *Listeria innocua* and *Brochothrix thermosphacta* in vacuum-packaged meat by addition of bacteriocinogenic *Lactobacillus curvatus* CRL705 and its bacteriocins," *Letters in Applied Microbiology*, vol. 43, no. 2, pp. 194–199, 2006.
- [27] R. H. Perez, T. Zendo, and K. Sonomoto, "Novel bacteriocins from lactic acid bacteria (lab): various structures and applications," *Microbial Cell Factories*, vol. 13, no. 1, p. S3, 2014.
- [28] J. Z. Acedo, M. J. van Belkum, C. T. Lohans, R. T. McKay, M. Miskolzie, and J. C. Vederas, "Solution structure of acidocin B, a circular bacteriocin produced by *Lactobacillus acidophilus* M46," *Applied and Environmental Microbiology*, vol. 81, no. 8, pp. 2910–2918, 2015.
- [29] M. A. Riley, "Bacteriocin mediated competitive interactions of bacterial populations and communities," in *Prokaryotic Antimicrobial Peptides*, D. Drider and S. Rebuffat, Eds., pp. 13–26, Springer, London, UK, 2011.
- [30] A. Savadogo, C. A. T. Ouattara, I. H. N. Bassole, and S. A. Traore, "Bacteriocins and lactic acid bacteria: a mini-review," *African Journal of Biotechnology*, vol. 5, pp. 678–683, 2006.
- [31] Y. Turovskiy, D. Kashtanov, B. Paskhover, and M. L. Chikindas, "Quorum sensing: fact, fiction, and everything in between," *Advances in Applied Microbiology*, vol. 62, no. 1, pp. 191–234, 2007.
- [32] J. Cleveland, T. J. Montville, I. F. Nes, and M. L. Chikindas, "Bacteriocins: safe, natural antimicrobials for food preservation," *International Journal of Food Microbiology*, vol. 71, no. 1, pp. 1–20, 2001.
- [33] I. F. Nes, D. B. Diep, and H. Holo, "Bacteriocin diversity in *Streptococcus* and *Enterococcus*," *Journal of Bacteriology*, vol. 189, no. 4, pp. 1189–1198, 2006.
- [34] I. F. Nes and V. G. H. Eijsink, "Regulation of group II peptide bacteriocin synthesis by quorum-sensing mechanisms," in *Cell-cell Signalling in Bacteria*, G. M. Dunny and S. C. Winans, Eds., pp. 175–192, American Society for Microbiology, Washington, DC, USA, 1999.
- [35] H. Lee and H. Y. Kim, "Lantibiotics, class I bacteriocins from the genus *Bacillus*," *Journal of Microbiology and Biotechnology*, vol. 21, no. 3, pp. 229–35, 2011.
- [36] M. P. Zacharof and R. W. Lovitt, "Bacteriocins produced by lactic acid bacteria a review article," *APCBEE Procedia*, vol. 2, pp. 50–56, 2012.
- [37] F. Guilhelmelli, N. Vilela, P. Albuquerque et al., "Antibiotic development challenges: the various mechanisms of action of antimicrobial peptides and of bacterial resistance," *Frontiers in Microbiology*, vol. 4, pp. 1–12, 2013.
- [38] L. M. Cintas, M. P. Casaus, C. Herranz, I. F. Nes, and P. E. Hernández, "Review: bacteriocins of lactic acid bacteria," *Food Science and Technology International*, vol. 7, no. 4, pp. 281–305, 2016.
- [39] G. Juodeikiene, E. Bartkiene, P. Viskelis et al., "Fermentation processes using lactic acid bacteria producing bacteriocins for preservation and improving functional properties of food products," in *Advances in Applied Biotechnology*, M. Petre, Ed., pp. 63–100, Intech, London, UK, 2012.
- [40] L. H. Deegan, P. D. Cotter, C. Hill, and P. Ross, "Bacteriocins: biological tools for bio-preservation and shelf-life extension," *International Dairy Journal*, vol. 16, no. 9, pp. 1058–1071, 2006.
- [41] O. Gillor, A. Etzion, and M. A. Riley, "The dual role of bacteriocins as anti- and probiotics," *Applied Microbiology and Biotechnology*, vol. 81, no. 4, pp. 591–606, 2008.
- [42] J. M. Willey and W. A. van der Donk, "Lantibiotics: peptides of diverse structure and function," *Annual Review of Microbiology*, vol. 61, no. 1, pp. 477–501, 2007.
- [43] Y. Sang and F. Blecha, "Antimicrobial peptides and bacteriocins: alternatives to traditional antibiotics," *Animal Health Research Reviews*, vol. 9, no. 2, pp. 227–235, 2008.
- [44] S. Gautam and N. Sharma, "Bacteriocin: safest approach to preserve food products," *Indian Journal of Microbiology*, vol. 49, no. 3, 2009.
- [45] C. V. Prudêncio, M. T. dos Santos, and M. C. D. Vanetti, "Strategies for the use of bacteriocins in gram-negative bacteria: relevance in food microbiology," *Journal of Food Science and Technology*, vol. 52, no. 9, pp. 5408–5417, 2015.
- [46] V. Bharti, A. Mehta, S. Singh et al., "Bacteriocin: a novel approach for preservation of food," *International Journal of Pharmacy and Pharmaceutical Sciences*, vol. 7, no. 9, pp. 20–29, 2015.
- [47] A. Gálvez, R. L. López, H. Abriouel, E. Valdivia, and N. B. Omar, "Application of bacteriocins in the control of foodborne pathogenic and spoilage bacteria," *Critical Reviews in Biotechnology*, vol. 28, no. 2, pp. 125–152, 2008.
- [48] B. C. Gomes, C. T. Esteves, I. C. V. Palazzo et al., "Prevalence and characterization of *Enterococcus* spp. isolated from

- Brazilian foods," *Food Microbiology*, vol. 25, no. 5, pp. 668–675, 2008.
- [49] B. Dal Bello, K. Rantsiou, A. Bellio et al., "Microbial ecology of artisanal products from North West of Italy and antimicrobial activity of the autochthonous populations," *LWT-Food Science and Technology*, vol. 43, no. 7, pp. 1151–1159, 2010.
- [50] M. P. Castro, N. Z. Palavecino, C. Herman, O. A. Garro, and C. A. Campos, "Lactic acid bacteria isolated from artisanal dry sausages: characterization of antibacterial compounds and study of the factors affecting bacteriocin production," *Meat Science*, vol. 87, no. 4, pp. 321–329, 2011.
- [51] F. P. Rivas, M. P. Castro, M. Vallejo, E. Marguet, and C. A. Campos, "Sakacin Q produced by *Lactobacillus curvatus* ACU-1: functionality characterization and antilisterial activity on cooked meat surface," *Meat Science*, vol. 97, no. 4, pp. 475–479, 2014.
- [52] N. M. Ali, S. Andleeb, B. Mazhar, I. Khadija, and B. Kalim, "Antibacterial activity and optimisation of bacteriocin producing lactic acid bacteria isolated from beef (red meat) samples," *Pakistan Journal of Scientific and Industrial Research, Series B: biological sciences*, vol. 59, no. 2, pp. 85–98, 2016.
- [53] S. Anastasiadou, M. Papagianni, G. Filiouis, I. Ambrosiadis, and P. Koidis, "Pediocin SA-1, an antimicrobial peptide from *Pediococcus acidilactici* NRRL B5627: production conditions, purification and characterization," *Bioresource Technology*, vol. 99, no. 13, pp. 5384–5390, 2008.
- [54] D. M. Müller, M. S. Carrasco, G. G. Tonarelli, and A. C. Simonetta, "Characterization and purification of a new bacteriocin with a broad inhibitory spectrum produced by *Lactobacillus plantarum* lp 31 strain isolated from dry-fermented sausage," *Journal of Applied Microbiology*, vol. 106, no. 6, pp. 2031–2040, 2009.
- [55] N. Sivakumar, Rajamani, and A.-B. Saif, "Partial characterization of bacteriocins produced by *Lactobacillus acidophilus* and *Pediococcus acidilactici*," *Brazilian Archives of Biology and Technology*, vol. 53, no. 5, pp. 1177–1184, 2010.
- [56] S. D. Todorov, P. Ho, M. Vaz-Velho, and L. M. T. Dicks, "Characterization of bacteriocins produced by two strains of *Lactobacillus plantarum* isolated from Beloura and Chourico, traditional pork products from Portugal," *Meat Science*, vol. 84, no. 3, pp. 334–343, 2010.
- [57] N. Ishibashi, K. Himeno, K. Fujita et al., "Purification and characterization of multiple bacteriocins and an inducing peptide produced by *Enterococcus faecium* NKR-5-3 from Thai fermented fish," *Bioscience, Biotechnology, and Biochemistry*, vol. 76, no. 5, pp. 947–953, 2014.
- [58] R. Szabóová, A. Lauková, M. P. Simonová, V. Strompfová, and L. Chrastinová, "Bacteriocin-producing enterococci from rabbit meat," *Malaysian Journal of Microbiology*, vol. 8, no. 4, pp. 211–218, 2012.
- [59] V. Biscola, S. D. Todorov, V. S. C. Capuano, H. Abriouel, A. Gálvez, and B. D. G. M. Franco, "Isolation and characterization of a nisin-like bacteriocin produced by a *Lactococcus lactis* strain isolated from charqui, a Brazilian fermented, salted and dried meat product," *Meat Science*, vol. 93, no. 3, pp. 607–613, 2013.
- [60] H. Zhang, L. Liu, Y. Hao et al., "Isolation and partial characterization of a bacteriocin produced by *Lactobacillus plantarum* BM-1 isolated from a traditionally fermented Chinese meat product," *Microbiology and Immunology*, vol. 57, no. 11, pp. 746–755, 2013.
- [61] W. Woraprayote, L. Pumpuang, A. Tosukhowong et al., "Two putatively novel bacteriocins active against Gram-negative food borne pathogens produced by *Weissella hellenica* BCC 7293," *Food Control*, vol. 55, pp. 176–184, 2015.
- [62] Y. An, Y. Wang, X. Liang et al., "Purification and partial characterization of M1-UVs300, a novel bacteriocin produced by *Lactobacillus plantarum* isolated from fermented sausage," *Food Control*, vol. 81, pp. 211–217, 2017.
- [63] I. Anacarso, L. Gigli, M. Bondi et al., "Isolation of two lactobacilli, producers of two new bacteriocin-like substances (BLS) for potential food-preservative use," *European Food Research and Technology*, vol. 243, no. 12, pp. 2127–2134, 2017.
- [64] Y. Hu, X. Liu, C. Shan et al., "Novel bacteriocin produced by *Lactobacillus alimentarius* FM-MM 4 from a traditional Chinese fermented meat Nanx Wudl: purification, identification and antimicrobial characteristics," *Food Control*, vol. 77, pp. 290–297, 2017.
- [65] X. Lv, H. Ma, M. Sun et al., "A novel bacteriocin DY4-2 produced by *Lactobacillus plantarum* from cutlassfish and its application as bio-preservative for the control of *Pseudomonas fluorescens* in fresh turbot (*Scophthalmus maximus*) fillets," *Food Control*, vol. 89, pp. 22–31, 2018.
- [66] M. D. Judge, E. D. Aberle, and J. C. Forrest, *Principles of Meat Science*, Kendall/Hunt Publishing Co., Dubuque, IA, USA, 3rd edition, 1989.
- [67] M. H. Eskandari, S. Hosseinpour, G. Mesbahi, and S. Shekarforoush, "New composite nitrite-free and low-nitrite meat-curing systems using natural colorants," *Food Science & Nutrition*, vol. 1, no. 5, pp. 392–401, 2013.
- [68] M. T. Duarte and K. F. Carrijo, "Quantificação do teor de nitrito de sódio residual em linguças cozidas tipo calabresa comercializadas no sul do estado do Rio de Janeiro, Brasil," *Enciclopédia Biosfera*, vol. 10, no. 19, pp. 1606–1615, 2014.
- [69] C. M. A. P. Franz, G. S. Cho, W. H. Holzapfel, and A. Gálvez, "Safety of lactic acid bacteria," in *Biotechnology of Lactic Acid Bacteria: Novel Applications*, F. Mozzi, R. R. Raya, and G. M. Vignolo, Eds., , pp. 341–359, 2010.
- [70] E. C. P. De Martinis, V. F. Alves, and B. D. G. M. Franco, "Fundamentals and perspectives for the use of bacteriocins produced by lactic acid bacteria in meat products," *Food Reviews International*, vol. 18, no. 2-3, pp. 191–208, 2002.
- [71] S. C. Yang, C. H. Lin, C. T. Sung, and J. Y. Fang, "Antibacterial activities of bacteriocins: application in foods and pharmaceuticals," *Frontiers in Microbiology*, vol. 5, p. 241, 2014.
- [72] V. Ahmad, M. S. Khan, Q. M. S. Jamal, M. A. Alzohairy, M. A. Al Karaawi, and M. U. Siddiqui, "Antimicrobial potential of bacteriocins: in therapy, agriculture and food preservation," *International Journal of Antimicrobial Agents*, vol. 49, no. 1, pp. 1–11, 2017.
- [73] R. P. Ross, M. Galvin, O. McAuliffe et al., "Developing applications for lactococcal bacteriocins," *Antonie van Leeuwenhoek*, vol. 76, no. 1–4, pp. 337–346, 1999.
- [74] T. D. Arthur, V. L. Cavera, and M. L. Chikindas, "On bacteriocin delivery systems and potential applications," *Future Microbiology*, vol. 9, no. 2, pp. 235–248, 2014.
- [75] P. Appendini and J. H. Hotchkiss, "Review of antimicrobial food packaging," *Innovative Food Science and Emerging Technologies*, vol. 3, no. 2, pp. 113–126, 2002.
- [76] M. S. Nascimento, I. Moreno, and A. Y. Kuaye, "Bacteriocins in food: a review," *Brazilian Journal of Food Technology, Campinas*, vol. 11, pp. 120–127, 2008.

- [77] B. K. Tiwari, V. P. Valdramidis, C. P. O' Donnell, K. Muthukumarappan, P. Bourke, and P. J. Cullen, "Application of natural antimicrobials for food preservation," *Journal of Agricultural and Food Chemistry*, vol. 57, no. 14, pp. 5987–6000, 2009.
- [78] L. A. Rogers, "The inhibitory effect of *Streptococcus lactis* on *Lactobacillus bulgaricus*," *Journal of Bacteriology*, vol. 16, no. 2, pp. 321–325, 1928.
- [79] L. J. Harris, H. P. Fleming, and T. R. Klaenhammer, "Developments in nisin research," *Food Research International*, vol. 25, no. 1, pp. 57–66, 1992.
- [80] J. Delves-broughton, "Nisin and its application as a food preservative," *International Journal of Dairy Technology*, vol. 43, no. 3, pp. 73–76, 1990.
- [81] A. Sobrino-López and O. Martín-Belloso, "Use of nisin and other bacteriocins for preservation of dairy products," *International Dairy Journal*, vol. 18, no. 4, pp. 329–343, 2008.
- [82] Y. M. Barboza, K. Ferrer, and E. M. Salas, "Combined effects of lactic acid and nisin solution in reducing levels of microbiological contamination in red meat carcasses," *Journal of Food Protection*, vol. 65, no. 11, pp. 1780–1783, 2002.
- [83] P. A. Maragkoudakis, K. C. Mountzouris, D. Psyrras et al., "Functional properties of novel protective lactic acid bacteria and application in raw chicken meat against *Listeria monocytogenes* and *Salmonella enteritidis*," *International Journal of Food Microbiology*, vol. 130, no. 3, pp. 219–226, 2009.
- [84] C. Dortu, M. Huch, W. H. Holzapfel, C. M. A. P. Franz, and P. Thonart, "Anti-listerial activity of bacteriocin-producing *Lactobacillus curvatus* CWBI-B28 and *Lactobacillus sakei* CWBI-B1365 on raw beef and poultry meat," *Letters in Applied Microbiology*, vol. 47, no. 6, pp. 581–586, 2008.
- [85] H. A. Hartmann, T. Wilke, and R. Erdmann, "Efficacy of bacteriocin-containing cell-free culture supernatants from lactic acid bacteria to control *Listeria monocytogenes* in food," *International Journal of Food Microbiology*, vol. 146, no. 2, pp. 192–199, 2011.
- [86] G.-S. Cho, A. Hanak, M. Huch, W. H. Holzapfel, and C. M. A. P. Franz, "Investigation into the potential of bacteriocinogenic *Lactobacillus plantarum* BFE 5092 for bio-preservation of raw Turkey meat," *Probiotics and Antimicrobial Proteins*, vol. 2, no. 4, pp. 241–249, 2010.
- [87] L. Díez, B. Rojo-Bezares, M. Zarazaga, J. M. Rodríguez, C. Torres, and F. Ruiz-Larrea, "Antimicrobial activity of pediocin PA-1 against *Oenococcus oeni* and other wine bacteria," *Food Microbiology*, vol. 31, no. 2, pp. 167–172, 2012.
- [88] M. Papagianni and S. Anastasiadou, "Pediocins: the bacteriocins of *Pediococci*. Sources, production, properties and applications," *Microbial Cell Factories*, vol. 8, no. 1, 3 pages, 2009.
- [89] D. L. Kalschne, S. Geitenes, M. R. Veit, C. M. P. Sarmiento, and E. Colla, "Growth inhibition of lactic acid bacteria in ham by nisin: a model approach," *Meat Science*, vol. 98, no. 4, pp. 744–752, 2014.
- [90] J. C. Nieto-Lozano, J. I. Reguera-Useros, M. d. C. Peláez-Martínez, G. Sacristán-Pérez-Minayo, Á. J. Gutiérrez-Fernández, and A. H. d. la Torre, "The effect of the pediocin PA-1 produced by *Pediococcus acidilactici* against *Listeria monocytogenes* and *Clostridium perfringens* in Spanish dry-fermented sausages and frankfurters," *Food Control*, vol. 21, no. 5, pp. 679–685, 2010.
- [91] Y. Kingcha, A. Tosukhowong, T. Zendo et al., "Anti-listeria activity of *Pediococcus pentosaceus* BCC 3772 and application as starter culture for nham, a traditional fermented pork sausage," *Food Control*, vol. 25, no. 1, pp. 190–196, 2012.
- [92] J. Zhang, G. Liu, P. Li, and Y. Qu, "Pentocin 31-1, a novel meat-borne bacteriocin and its application as biopreservative in chill-stored tray-packaged pork meat," *Food Control*, vol. 21, no. 2, pp. 198–202, 2010.
- [93] S. Smaoui, L. Elleuch, R. Ben Salah et al., "Efficient role of BacTN635 on the safety properties, sensory attributes, and texture profile of raw minced meat beef and chicken breast," *Food Additives and Contaminants: Part A*, vol. 31, no. 2, pp. 218–225, 2014.
- [94] A. Chakchouk-mtibaa, S. Smaoui, N. Ktari et al., "Bio-preservative efficacy of bacteriocin BacFL31 in raw ground Turkey meat in terms of microbiological, physicochemical, and sensory qualities," *Biocontrol Science*, vol. 22, no. 2, pp. 67–77, 2017.
- [95] S. V. Moracanin, L. Turubatovic, M. Skrinjar, and D. Obradovic, "Antilisterial activity of bacteriocin isolated from *Leuconostoc mesenteroides* ssp. *mesenteroides* IMAU: 10231 in the production of sremeska sausages: lactic acid bacteria isolation, bacteriocin identification and meat application experiments," *Food Technology and Biotechnology*, vol. 51, no. 2, pp. 247–256, 2013.
- [96] M. Papagianni and D. Sergelidis, "Effects of the presence of the curing agent sodium nitrite, used in the production of fermented sausages, on bacteriocin production by *Weissella paramesenteroides* DX grown in meat simulation medium," *Enzyme and Microbial Technology*, vol. 53, no. 1, pp. 1–5, 2013.
- [97] N. P. Guerra, C. L. Macias, A. T. Agrasar, and L. P. Castro, "Development of a bioactive packaging cellophane using NisaplinR as biopreservative agent," *Letters in Applied Microbiology*, vol. 40, no. 2, pp. 106–110, 2005.
- [98] E. Kristo, K. P. Koutsoumanis, and C. G. Biliaderis, "Thermal, mechanical and water vapor barrier properties of sodium caseinate films containing antimicrobials and their inhibitory action on *Listeria monocytogenes*," *Food Hydrocolloids*, vol. 22, no. 3, pp. 373–386, 2008.
- [99] C. E. Realini and B. Marcos, "Active and intelligent packaging systems for a modern society," *Meat Science*, vol. 98, no. 3, pp. 404–419, 2014.
- [100] J. P. Kerry, M. N. O'Grady, and S. A. Hogan, "Past, current and potential utilisation of active and intelligent packaging systems for meat and muscle-based products: a review," *Meat Science*, vol. 74, no. 1, pp. 113–130, 2006.
- [101] C. H. Lee, D. S. An, H. J. Park, and D. S. Lee, "Wide-spectrum antimicrobial packaging materials incorporating nisin and chitosan in the coating," *Packaging Technology and Science*, vol. 16, no. 3, pp. 99–106, 2003.
- [102] M. Ye, H. Neetoo, and H. Chen, "Control of *Listeria monocytogenes* on ham steaks by antimicrobials incorporated into chitosan-coated plastic films," *Food Microbiology*, vol. 25, no. 2, pp. 260–268, 2008.
- [103] Z. K. Emiroglu, G. P. Yemis, B. K. Coskun, and K. Candogan, "Antimicrobial activity of soy edible films incorporated with thyme and oregano essential oils on fresh ground beef patties," *Meat Science*, vol. 86, no. 2, pp. 283–288, 2010.
- [104] K. K. Kuorwel, M. J. Cran, K. Sonneveld, J. Miltz, and S. W. Bigger, "Essential oils and their principal constituents as antimicrobial agents for synthetic packaging films," *Journal of Food Science*, vol. 76, no. 9, pp. R164–R177, 2011.
- [105] A. La Stora, G. Mauriello, F. Villani, and D. Ercolini, "Coating-activation and antimicrobial efficacy of different

- polyethylene films with a nisin-based solution,” *Food and Bioprocess Technology*, vol. 6, no. 10, pp. 2770–2779, 2012.
- [106] X. Ming, G. H. Weber, J. W. Ayres, and W. E. Sandine, “Bacteriocins applied to food packaging materials to inhibit *Listeria monocytogenes* on meats,” *Journal of Food Science*, vol. 62, no. 2, pp. 413–415, 1997.
- [107] P. Santiago-Silva, N. F. F. Soares, J. E. Nóbrega et al., “Antimicrobial efficiency of film incorporated with pediocin (ALTA 2351) on preservation of sliced ham,” *Food Control*, vol. 20, no. 1, pp. 85–89, 2009.
- [108] B. Marcos, T. Aymerich, J. M. Monfort, and M. Garriga, “Use of antimicrobial biodegradable packaging to control *Listeria monocytogenes* during storage of cooked ham,” *International Journal of Food Microbiology*, vol. 120, no. 1-2, pp. 152–158, 2007.
- [109] O. Osmanagaoglu, F. Kiran, and H. Ataoglu, “Evaluation of in vitro probiotic potential of *Pediococcus pentosaceus* OZF isolated from human breast milk,” *Probiotics and Antimicrobial Proteins*, vol. 2, no. 3, pp. 162–174, 2010.
- [110] A. Swetwathana and W. Visessanguan, “Potential of bacteriocin-producing lactic acid bacteria for safety improvements of traditional Thai fermented meat and human health,” *Meat Science*, vol. 109, pp. 101–105, 2015.
- [111] A. Swetwathana, N. Lotong, J. Nakayama, and K. Sonomoto, “Maturation of Nham—a Thai fermented meat product: effect of pediocin PA-1 producer (*Pediococcus pentosaceus* TISTR 536) as starter culture, nitrite and garlic on *Salmonella anatum* during Nham fermentation,” *Fleischwirtschaft International*, vol. 22, no. 3, pp. 46–49, 2007.
- [112] P. P. Vijayakumar and P. M. Muriana, “Inhibition of *Listeria monocytogenes* on ready-to-eat meats using bacteriocin mixtures based on mode-of-action,” *Foods*, vol. 6, no. 22, 2017.



Hindawi

Submit your manuscripts at
www.hindawi.com

