

Review

Smoked Salmon: Intersection of Tradition, Safety, *Listeria monocytogenes*, and the Role of Bacteriocins in Biopreservation

Thyago Matheus Wojcik ¹, Emília Maria França Lima ¹ , Dmitry Rudoy ² , Alexey Ermakov ³, Besarion Meskhi ² , Kirill Alexandrovich Lubchinsky ⁴, Valentina Nikolaevna Khramova ⁴ , Alan Khoziev ⁵, Amina Sergoevna Dzhaboeva ⁶, Yulia Aleksandrovna Kumysheva ⁶, Oleg V. Mitrokhin ⁷ , Mohamed Merzoug ⁸ , Manuela Vaz-Velho ⁹ , Iskra Vitanova Ivanova ¹⁰ and Svetoslav Dimitrov Todorov ^{1,7,9,10,*} 

- ¹ ProBacLab, Laboratório de Microbiologia de Alimentos, Departamento de Alimentos e Nutrição Experimental, Food Research Center, Faculdade de Ciências Farmacêuticas, Universidade de São Paulo, São Paulo 05508-000, Brazil; thyago.wojcik013@gmail.com (T.M.W.); emiliamflima@usp.br (E.M.F.L.)
- ² Agribusiness Faculty, Don State Technical University, Gagarin Square 1, 344000 Rostov-on-Don, Russia; rudoy.d@gs.donstu.ru (D.R.); spu-02@donstu.ru (B.M.)
- ³ Institute of Life Sciences, Don State Technical University, Gagarin Square 1, 344000 Rostov-on-Don, Russia; amermakov@ya.ru
- ⁴ Department of Food Production Technology, Volgograd State Technical University, V.I. Lenin Avenue, 28, 400005 Volgograd, Russia; lubkirill@mail.ru (K.A.L.); hramova_vn@mail.ru (V.N.K.)
- ⁵ Department of Biotechnology and Standardization, Federal State Budgetary Institution of Higher Education, Gorsky State Agrarian University, 362000 Vladikavkaz, Russia; hoziev_alan@mail.ru
- ⁶ Department of Food Technology and Chemistry, Federal State Budgetary Educational Institution of Higher Education, V.M. Kokov Kabardino-Balkarian State Agrarian University, 360000 Nalchik, Russia; tpop_kbr@mail.ru (A.S.D.); ykumysheva@mail.ru (Y.A.K.)
- ⁷ Department of General Hygiene, Sechenov First Moscow State Medical University, Trubetskaya Str. 8, Bldg. 2, 119991 Moscow, Russia; mov1163@yandex.ru
- ⁸ Higher School of Biological Sciences of Oran, BP 1042 Saim Mohamed, Cité Emir Abdelkader (EX-INNESSMO), Oran 31000, Algeria; merzoug.mohamed1@yahoo.fr
- ⁹ CISAS—Center for Research and Development in Agrifood Systems and Sustainability, Instituto Politécnico de Viana do Castelo, 4900-348 Viana do Castelo, Portugal; mvazvelho@estg.ipvc.pt
- ¹⁰ Department of General and Applied Microbiology, Faculty of Biology, Sofia University, St. Kliment Ohridski, 8 Dragan Tzankov Blvd., 1164 Sofia, Bulgaria; iskrai3@yahoo.com
- * Correspondence: slavi310570@abv.bg or todorov@usp.br; Tel.: +55-11-9-6306-2012

Abstract

Lactic acid bacteria (LABs) produce bacteriocins, which are increasingly recognized as effective biopreservatives for smoked salmon. These bacteriocins may help solve the ongoing problem of controlling *Listeria monocytogenes* in the smoked salmon industry. *L. monocytogenes* is a psychrotolerant, salt-tolerant foodborne pathogen capable of surviving the refrigerated, low-oxygen conditions typical of smoked salmon processing. Its presence poses significant public health risks, particularly for immunocompromised individuals, and continues to drive costly product recalls and regulatory pressure. Conventional control strategies, including chemical preservatives and physical treatments, are increasingly limited by consumer demand for clean-label foods and the pathogen's ability to persist in processing environments. The bacteriocins produced by LABs provide a precise and natural alternative to conventional preservatives. These antimicrobial peptides can inhibit *L. monocytogenes* through membrane disruption and metabolic interference while maintaining the sensory quality of smoked salmon. Their application in surface treatments, protective coatings, and active packaging has demonstrated strong potential to suppress pathogen growth during chilled storage. As the smoked salmon industry is seeking sustainable and effective biocontrol tools, bacteriocins represent a viable strategy to enhance product safety, extend shelf life, and reduce reliance on synthetic additives. Continued



Academic Editor: Wenzheng Shi

Received: 23 January 2026

Revised: 16 February 2026

Accepted: 25 February 2026

Published: 20 March 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article

distributed under the terms and

conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)

[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

research into their stability, delivery systems, and synergistic combinations will be essential for integrating bacteriocins into modern smoked salmon preservation frameworks.

Keywords: smoked salmon; bacteriocins; biopreservation; food safety; *Listeria monocytogenes*

Key Contribution: Smoked salmon is a popular food product among consumers; however, it can serve as a carrier for *L. monocytogenes*, a foodborne pathogen. Bacteriocins produced by LAB offer a potential solution for reducing or even eliminating *L. monocytogenes* in smoked salmon, making them an effective biopreservative.

1. Introduction

Nutrition was recognized as an important scientific discipline in the last century, reflecting the fundamental need for quality food products. Previous compromises in the quality and safety of food products were often linked to corporate or personal profit motives. However, over the last century, various government agencies and scientific organizations have promoted the idea that food should not only be nutritious and safe but also offer additional health benefits [1]. At present, food products are not simply nutritional commodities; they play an essential, scientifically proven role in providing bioactive components that are important for wellbeing and contribute to preventive medicine [2]. Enriching food products with beneficial microbial cultures or supporting the natural presence of beneficial microorganisms in fermented food products exemplifies the intersection of nutrition and the probiotic concept [3]. At the beginning of the 20th century, Ilia Metchnikoff and his collaborator Stamen Grigorov postulated that the lactic acid bacteria (LAB) in fermented dairy products provide essential benefits for human health. At the same time, in Japan, Minoru Shirota established the scientific fundamentals of the preventive nutritional role of LABs and the consumption of fermented milk, subsequent to which Yakult products were developed [4]. In early industry investigations, various LAB strains were identified and developed for use as probiotics. The concept of probiotics has since been reconsidered, leading to the proposal of the term “New-Generation Probiotics.” This refers to distinct microbial species, different from those traditionally recognized, which are framed as important contributors to the health of humans and other animals. The term postbiotics has also been introduced, which describes non-viable cells whose beneficial effects are attributed to the metabolites produced by microbial cultures [5].

2. Bacteriocins: Almost a Century of History

In 1925, Gratia observed, described, and introduced the scientific community to the beneficial role of antimicrobial peptides (bacteriocins) of *Escherichia coli* as potential antimicrobials [6]. In 1933, the first bacteriocin from LABs was reported, marking the beginning of application of bacteriocins as valuable contributors to the biopreservation of food products. Although colicin was the first bacteriocin reported in the literature [6], nisin, the second bacteriocin reported, attracted greater scientific attention, likely because it was produced by *Lactococcus lactis*, an LAB, which is considered a safe microbial species. Its discovery was significant because it is one of the earliest examples of a naturally occurring antimicrobial peptide reported, predating widespread antibiotic use.

Initial studies with nisin focused on its specific antibacterial spectrum, which was particularly effective against Gram-positive bacteria such as those from the genera *Clostridium* and *Listeria*, which are both considered relevant to spoilage in the food industry [7]. Bacteriocins are antimicrobial peptides that are produced through ribosomal synthesis by various microorganisms, including Gram-positive and Gram-negative bacteria, as well as

Archaea and some eukaryotes. Early studies on bacteriocins centered on their use in food biopreservation [8]. However, later investigations found that the application of bacteriocins, including nisin, can extend beyond food additives contributing to food safety to pharmaceutically active metabolites that play an essential role in controlling antibiotic-resistant pathogens [6], whether used as individual agents or in synergistic interactions with antibiotics [9,10]. Moreover, modifications in the primary structure of nisin showed the potential to improve its spectrum of activity and even its potential use in the treatment of *Mycobacterium tuberculosis* [11,12].

It is relevant to emphasize that, along with nisin, a subject of early research on bacteriocins, later, several other bacteriocins were characterized as antimicrobials with impressive heat stability and activity at very low concentrations, characteristics that distinguished them from many other natural antimicrobials [6]. These properties can be attributed to their reasonably low molecular mass, which is normally below 5 kDa [8]. By the 1950s, commercial production of nisin began under the name Nisaplin[®], and nisin was soon recognized as a safe food preservative by the EFSA and the FDA [13].

Nisin's ability to extend shelf life without altering flavor or texture made it invaluable in the production of dairy, canned foods, and meat products [13]. Its low cytotoxicity, reported to be approximately the same as sodium chloride (NaCl), with an estimated lethal dose (LD50) of 6950 mg/kg [14], was an additional argument for the food industry to explore nisin as an effective biopreservative in processed food products. It was the first bacteriocin widely applied in the food industry, and by the late 1960s, it had been approved as a food additive in multiple countries.

Beyond its use in the food industry as a biopreservative, nisin served as a model system for lantibiotics, a class of antimicrobial peptides characterized by unusual amino acids and extensive post-translational modifications [6]. Initial genetic and biochemical investigations into nisin biosynthesis have advanced our understanding of gene regulation and peptide engineering within prokaryotic systems [15]. This research laid the foundation for exploring other bacteriocins and understanding microbial competition at the molecular level. The pioneering work on nisin demonstrated that naturally occurring peptides could be harnessed for both practical applications and advancing fundamental science. Its discovery and early characterization not only safeguarded food supplies but also opened new avenues in microbiology, biotechnology, and antimicrobial research [6–8].

The biological benefit of bacteriocins is primarily due to the fact that they provide better chances for the host to gain a competitive advantage in their ecological niche over other microorganisms. Thus, according to Chikindas et al. [16], that their primary targets are closely related to the producer microbial group is because they have same requirements for environmental and nutritional conditions. Unlike broad-spectrum antibiotics, bacteriocins typically exhibit narrow-spectrum activity, targeting strains that are genetically similar to the producer organism [17]. This specificity allows bacteria to suppress competitors without disrupting entire microbial communities; as a result, bacteriocins are promising candidates for precise antimicrobial interactions with high specificity [6]. In addition to having a very specific antimicrobial spectrum of activity, in recent decades, some evidence has emerged for an unspecific spectrum of activity. For example, some bacteriocins produced by LABs (Gram-positive producers) expressing activity against Gram-negative bacteria, viruses, yeasts, and even mycobacteria [18]. Furthermore, Chikindas et al. [16] suggested that the antimicrobial properties of bacteriocins should be regarded as secondary assets for these peptides, as their primary biological role likely relates to *quorum sensing* and other interactions between microbial cells.

Tagg et al. [19] provided one of the earliest definitions and classifications of bacteriocins, recognizing them as a group with significant structural and functional diversity.

Over time, various classifications of bacteriocins have been suggested. However, it is generally agreed that bacteriocins are small peptides produced by the cell's ribosomal machinery. Some may also be larger protein complexes or include non-protein compounds that contribute to their activity [19]. The mechanisms by which bacteriocins exert their effects are diverse; however, principal strategies encompass membrane pore formation, inhibition of cell wall synthesis, and disruption of critical enzymatic processes [8] (see Figure 1).

In Tagg et al.'s broadly accepted classification [19], LAB bacteriocins are divided into three major classes based on their biochemical properties, molecular weight, and mode of action. This framework, which groups bacteriocins into broad classes that reflect their structural and functional characteristics, has remained fundamental in bacteriocin systematics, even though later refinements expanded the categories and some other classifications have been proposed. Class I is dedicated to the group of lantibiotics described as small peptides (<5 kDa), which undergo extensive post-translational modifications and contain some unusual amino acids such as lanthionine and methyllanthionine. An iconic representative from this group is nisin, the first and most studied lantibiotic, which binds to the lipid II of target cells and disrupts cell wall synthesis through modes of action including pore formation and the inhibition of peptidoglycan biosynthesis.

In Tagg et al.'s framework, Class II bacteriocins [19] are small, heat-stable, non-lantibiotic peptides, usually smaller than 10 kDa, without extensive modifications. This group is subdivided into Class IIa, which comprise Pediocin-like bacteriocins with specific strong activity against *Listeria*. These bacteriocins have a specific conservative amino acid fragment (YGNGV/L) 'pediocin box' motif, which is responsible for their specific anti-*Listeria* activity [20].

In the same class of bacteriocins, subclass IIb comprises two-peptide bacteriocins that are involved in synergistic interactions. These bacteriocins require both components for functional activity [7]. Subclass IIc bacteriocins have a circular molecular structure and enhanced stability. The most known representative of this group is enterocin AS48, a well-studied bacteriocin with membrane permeabilization and pore formation modes of action [21].

Class III bacteriocins are large, heat-labile proteins which typically have a high molecular weight (>30 kDa). Taking their molecular weight into consideration, it is not surprising that they are often sensitive to heat and proteolytic enzymes. Helveticin J is one of the most extensively studied Class III bacteriocins. Notably, helveticin J demonstrates a unique mode of action that involves the enzymatic degradation of components within the target cell. This specific activity contributes to its ability to disrupt essential cellular functions in susceptible microorganisms, ultimately leading to cell death [22,23].

Most bacteriocins, such as nisin, interact with and disrupt the cell membrane, causing leakage of essential intracellular components and resulting in cell death. Moreover, the majority of bacteriocins are characterized as cationic and amphipathic polypeptides, characteristics that allow them to bind to negatively charged bacterial membranes [20] (Figure 1). Evaluating the mode of action of nisin shows that its bacteriocins use lipid II as a receptor via their N-terminus, followed by insertion of their C-terminus into the cell membrane. Once inserted into the lipid bilayer, the bacteriocin causes the formation of pores that cause leakage of ions, ATP, and other vital molecules [20]. Certain bacteriocins, particularly pediocin-like bacteriocins (Class II), target the mannose phosphotransferase system (Man-PTS) associated with the cell envelope, similarly creating pores in the cell membrane [22], as illustrated in Figure 1. The formation of such as channels leads to rapid depolarization and cell death. Additionally, it was shown that certain bacteriocins may in-

terfere with cell wall precursor molecules, such as lipid II, preventing proper peptidoglycan synthesis, which weakens the bacterial cell wall [24] (Figure 1).

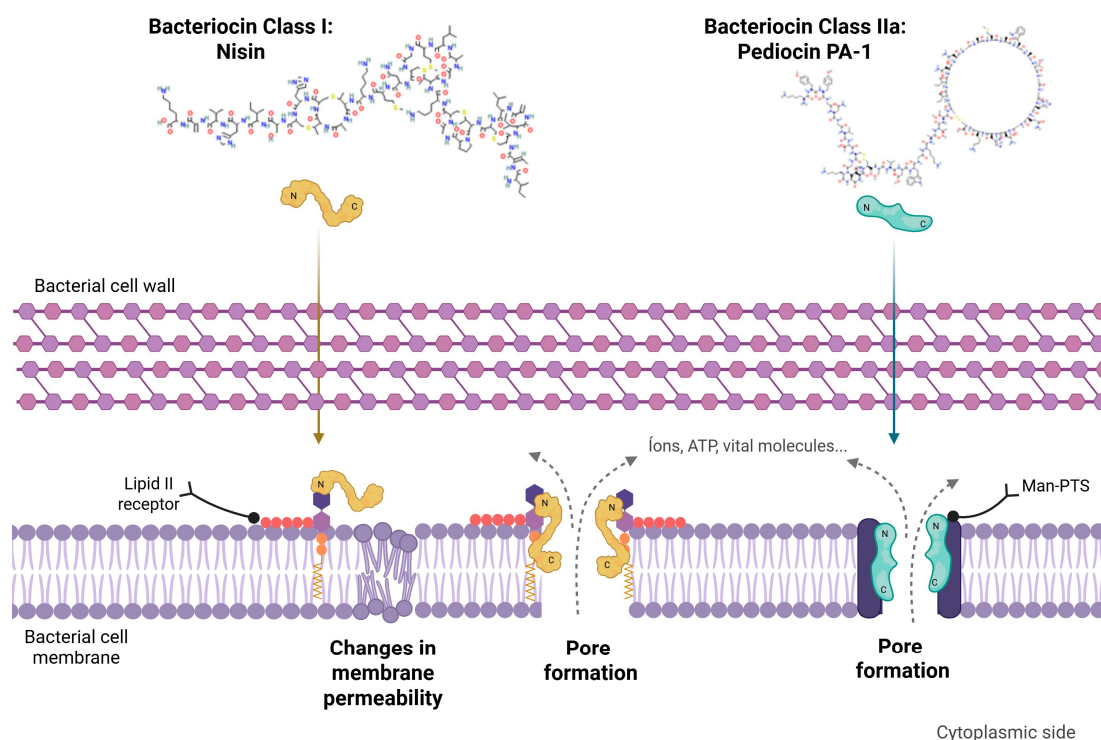


Figure 1. Mode of action of bacteriocins in Gram-positive bacteria. Bacteriocins, such as nisin (class I bacteriocin) and pediocin (class IIa bacteriocin), target the cell wall. Nisin primarily binds to Lipid II, which inhibits cell wall biosynthesis, facilitating membrane insertion and pore formation. Pediocin-like bacteriocins often use specific membrane receptors (Man-PTS components) to induce pore formation. This process causes the efflux of vital intracellular molecules, leading to cell death. (Figure created in BioRender. Lima, E. (2026) <https://BioRender.com/q0n0mfg>, accessed on 5 January 2026). Based on studies by Aguirre-Garcia et al. [22] and Rani et al. [25]. Arrows present way of bacteriocins via cell wall.

Some bacteriocins may use already existing channels in the cell wall to penetrate the target cell and interact with/interrupt certain essential enzyme or nucleic acid functions. These processes can block DNA replication or RNA transcription, consequently halting the growth and division of microbial cells [26,27].

It is important to emphasize that most bacteriocin-producing microorganisms are immune to their own bacteriocins, as the producing bacteria carry immunity proteins that protect them. This specificity ensures a competitive advantage without self-damage [24].

3. *Listeria monocytogenes*: Built to Survive

Research on *L. monocytogenes* has a fairly short scientific history. The earliest reports date back to 1924, when Gram-positive rods isolated from the blood of laboratory rabbits that had died suddenly were reported by E.G.D. Murray, a bacteriologist from Cambridge [28]. This new species was initially named *Bacterium monocytogenes*, but in 1940, it was renamed *L. monocytogenes* by Harvey Pirie in honor of Joseph Lister [28]. *L. monocytogenes* received scientific attention as cases of listeriosis have been reported worldwide, in association with different food products, including cheese, meat, seafood, vegetables, and fruits [28]. It is interesting to note that *L. monocytogenes* has a unique physiology making it a resilient foodborne pathogen that is highly adaptable to different environmental conditions. Some of its physiological characteristics include growth in

a wide temperature range (from -0.4°C to 45°C , with an optimal temperature of 37°C), resistance to a wide range of pH levels (from 4.5 to 9.5), and the ability to tolerate salt concentrations of up to 20%. Compared to other foodborne pathogens, it is relatively unaffected by reductions in water activity ($a_w < 0.90$) [29]. Moreover, *L. monocytogenes* has the ability to form biofilms and can move intracellularly in host cells by utilizing actin filaments [28,29].

In 2016, Orsi and Wiedmann suggested a reclassification of the genus *Listeria*, defining four new genera: genus *Listeria*, harboring *L. monocytogenes*; *Listeria mathii*; *Listeria innocua*; *Listeria welshmerii*; *Listeria ivanovii*; and *Listeria seelgeri*. Among these genera, only *L. monocytogenes* is considered a human pathogen, while *L. ivanovii* is a pathogen for animals [28]. In Orsi and Wiedmann's proposal [30], *Listeria grayi* was reclassified as *Murraya grayi*, while *Listeria fleischmannii*, *Listeria floridensis*, and *Listeria aquatica* were reclassified as *Mesolisteria*. Other previously reported representatives from the genus *Listeria* (*Listeria newyorkensis*, *Listeria cornellensis*, *Listeria rocouitiae*, *Listeria weihenstephanensis*, *Listeria grandensis*, *Listeria riparia*, and *Listeria booriae*) were reclassified as genus *Paenilisteria* [30].

L. monocytogenes in particular has been the subject of extensive research. Based on whole-genome single nucleotide polymorphism (SNP) genotyping, the species was grouped into the four divergent evolutionary lineages (I to IV) and can be further subdivided into sub-lineages (SLs), 14 serotypes (i.e., 1/2a, 1/2b, 1/2c, 3a, 3b, 3c, 4a, 4ab, 4b, 4c, 4d, 4e, 4h and 7), and sequence types (STs), which are then grouped into clonal complexes (CCs) and classified using core-genome multi-locus sequence typing (cgMLST or CT) [28]. It is noteworthy that even if all *L. monocytogenes* strains are considered potentially pathogenic, detailed investigations based on epidemiological and experimental evidence indicate that three specific serotypes (1/2a-lineage II, 1/2b, and 4b-lineage I) are associated with 92% to 95% of human clinical isolates. Interestingly, Lineage II isolates are mostly associated with food, whereas lineage I isolates are predominantly linked to clinical cases in Western countries. Data from China and Taiwan show that 1/2b is the most prevalent serotype in both food and clinical cases [28].

L. monocytogenes is clearly associated with foodborne infections. Preventing contamination involves disconnecting its natural reservoirs from the food supply and using multiple interventions during production. Strict hygiene; proper handling, storage, and cooking; and regular sanitization are vital to preventing external and cross-contamination, especially after processing. Maintaining high standards reduces risks introduced by raw ingredients, equipment, and personnel. Different governmental and international agencies have established regulations and standards for the presence of *L. monocytogenes* in the food industry.

The World Health Organization (WHO), the Food and Agriculture Organization (FAO), and Codex Alimentarius Commission (CAC) developed "Guidelines on the Application of General Principles of Food Hygiene to the Control of *L. monocytogenes* in Foods". These guidelines offer informed recommendations for governments worldwide for controlling *L. monocytogenes* in ready-to-eat products, with the objective of safeguarding public health and upholding equitable food trade practices [31,32].

The CAC recommendations categorize ready-to-eat foods into two groups, in which growth conditions for *L. monocytogenes* are the primary factor when evaluating risk. For food products in which growth can occur, the microbiological criterion is absence in 25 g (<0.04 CFU/g). In this scenario, the relevant food products are defined as at risk for a greater average increase of 0.5 log Colony-Forming Units (CFU)/g of *L. monocytogenes* over the course of their expected shelf life, distribution, and storage. Moreover, for ready-to-eat

foods in which growth will not occur, the microbiological criteria is set at 100 CFU/g, since there is no evidence that *L. monocytogenes* can multiply during the products' shelf lives [32].

The FDA previously (2008–2017) had a limit of 100 CFU/g in ready-to-eat (RTE) food that did not support the growth of *L. monocytogenes*. However, after some outbreaks of listeriosis in 2015 were attributed to ice cream, which is considered an RTE food that does not support growth of this pathogen, and considering the low contamination level of *L. monocytogenes* (0.15–7.1 MNP/g), the agency decided to reinstate a zero-tolerance policy for all RTE foods [33–35]. Similarly, the European Union enforces a zero-tolerance policy for the presence of *L. monocytogenes* in dairy and ready-to-eat products before foods leave the immediate control of the establishment that produced them (Commission regulation (EC) N° 2073/2005, amended in 2020). It is important to note that EU regulations tolerate levels below 100 CFU/g for foods other than those intended for infants and special medical purposes [36,37].

4. Smoked Salmon Production: Economic and Production Perspectives

The practice of processing food is as old as human civilization. Preserving excess food by processing was necessary to prepare for periods of insufficient food supply. Thus, different fermentation methods were developed empirically and incorporated into food preparation processes. Smoking is perhaps one of the oldest known preservation processes. The history of smoking meat and fish, including salmon, for preservation stretches back thousands of years. Civilizations were settled and developed near sources of water, and fish was one of the proteins regularly consumed by humans. Ancient civilizations appreciated smoked fish as a preserved food. During the middle ages, smoked fish was integrated into European diets, often as an accessible protein source. However, during the Victorian era, smoked products transitioned from survival foods to luxury items served at royal meals and elite gatherings. This shift marked the beginning of smoked salmon's association with prestige and fine dining [38].

In this period (19th century and beginning of 20th century), the sale of smoked salmon expanded significantly in parallel with improved smoking techniques and cold chain logistics that enabled salmon to be traded across borders. During this time, Scotland and Norway emerged as major centers of smoked salmon production, exporting the product that became a symbol of wellbeing and luxury in Europe and North America [38].

The development of aquaculture as a form of sustainable fish production in the late 20th century and beginning of the 21st century has further transformed the industrial production of smoked salmon, enabling consistent supply and global distribution. In the last century, genetically modified salmon were introduced into industrial salmon production. The predominant genetically engineered salmon was AquAdvantage Salmon, developed by AquaBounty Technologies (Maynard, MA, USA) in 1989, which marked a significant milestone in biotechnology and aquaculture (<https://www.fda.gov/animal-veterinary/aquadvantage-salmon/aquadvantage-salmon-fact-sheet>, accessed on 5 January 2026). This salmon was developed by AquaBounty Technologies by inserting a growth hormone gene from Pacific Chinook salmon and a promoter sequence from ocean pout into the Atlantic salmon's DNA. The intent of the modification was to ensure the salmon could produce growth hormone throughout the year rather than only seasonally, allowing it to reach market size in about half the time required by conventional farmed salmon. While traditional Atlantic salmon typically require close to thirty months to mature, AquAdvantage salmon can be harvested in sixteen to eighteen months, offering substantial economic advantages by reducing feed costs and shortening production cycles [39,40].

The U.S. FDA approved AquAdvantage Salmon in 2015 after evaluating its safety for human consumption, its environmental impact, and the health impact on the fish

itself. To reduce ecological risks, the fish need to be raised on land-based controlled farms. Moreover, it was engineered to be sterile, minimizing the possibility of interbreeding with wild populations. These measures were implemented as preventative actions to ensure that genetically modified salmon do not disrupt natural ecosystems.

From an economical perspective, the faster growth rate and reduced resource requirements make genetically modified salmon attractive for aquaculture at industrial scales, where feed represents the largest cost driver. Although genetically modified salmon has been recognized for its economic efficiency, it remains the subject of significant debate. Opponents raise concerns about the risk of ecological safety should containment measures fail. Moreover, consumer acceptance remains mixed regarding genetically modified products. Importantly, the European Union has not approved genetically modified salmon for sale, citing ethical and environmental reservations. Although the engineered fish has been approved by the FDA, its distribution in North America remains limited due to regulatory hurdles and consumer skepticism.

Smoked salmon is both an emblem of culinary sophistication and a multi-billion-Euro global trade commodity, illustrating its evolution from a traditional preserved food to a contemporary luxury item. Over the last century, smoked salmon production has represented one of the most dynamic segments of the global seafood industry, incorporating traditional culinary practices and modern aquaculture and processing technologies.

The global smoked salmon market was estimated at around 5.0 billion Euro in 2023 and is projected to reach around 8.0 billion Euro by 2032, a projected annual growth rate of nearly six percent (<https://www.businessresearchinsights.com/market-reports/smoked-salmon-market-120069>, accessed on 5 January 2026). The consumption of smoked salmon is clearly related to shifting dietary preferences, specifically associated with the health benefits of its omega-3 content.

Europe remains one of the largest consumer markets for smoked salmon, where the United Kingdom, France, and Germany consume the most of both cold- and hot-smoked varieties. Smoked salmon consumption is steady in North America, particularly in food service and premium retail channels. The Asia-Pacific region is one of the fastest-growing regions for smoked salmon consumption, which is clearly associated with rising middle-class incomes and expanding retail distribution networks.

Retail-available salmon, including smoked salmon, comes from two primary sources—farmed and wild salmon. In the last 50 years, due to concern for environmental protection and sustainability, farmed salmon accounts for the majority of the supply, offering stability, consistency in quality, and volume while reducing costs compared to wild-caught alternatives. However, the previously noted concern over the use of genetically modified salmon in farming is the subject of consumer complaints. Wild salmon, which has a smaller share from the commercial point of view, is marketed as a premium product, often commanding higher prices due to its perceived natural origin and seasonal availability. Transformation of the raw fish material to the final smoked product can be achieved with different processing methods, with cold smoking and hot smoking representing the two dominant techniques applied in the food industry. Cold smoking preparation involves curing and smoking at a temperature of 20–30 °C and results in a more delicate texture and flavor in the final product. In contrast “hot smoking”, is performed at 50–80 °C and yields a firmer product, which looks like it has been cooked [41]. In both production approaches, it is crucial to control the salting, brining, and smoking environments to ensure food safety, flavor consistency, and compliance with regulatory standards [41].

5. Regulatory Frameworks and Safety Measures

With increasing consumption of smoked salmon, production must rise to meet market demand. However, there are significant microbial safety challenges associated with smoked salmon, relating to the specificity of the raw material, method of processing, and distribution of the final product. It is very important to specify that cold-smoked salmon undergoes industrialized processing at low temperatures (18–28 °C), which do not eliminate pathogens; moreover, they can facilitate multiplication of several common foodborne pathogens [42]. After cold smoking, the product is kept at refrigeration temperature during distribution. However, *L. monocytogenes*, a foodborne pathogen, is capable of surviving and proliferating under refrigeration, representing a risk that persists throughout the product's shelf life [29].

Other concerns include another foodborne pathogen, *Clostridium botulinum*, especially in vacuum-packed products, where anaerobic conditions can promote the production of toxins by this pathogen. Other groups of spoilage organisms, such as LABs, can be factors that may influence organoleptic properties of the smoked salmon. Moreover, contaminations with *Pseudomonas* spp. may have serious consequences for the organoleptic properties and health of the consumers [43].

According to safety regulations in the European Union, microbial safety standards for smoked salmon are described in Regulation (EC) No 2073/2005, which stipulates that *L. monocytogenes* must not exceed 100 CFU/g during the product's shelf life. Moreover, producers are expected to validate shelf-life studies and implement Hazard Analysis and Critical Control Points (HACCP) systems. The FDA in the USA enforces a zero-tolerance policy for *L. monocytogenes* in ready-to-eat foods, as outlined in the Fish and Fishery Products Hazards and Controls Guidance [13]. In some specific national regulation documents, such as the Food Safety Authority of Ireland, additional guidance focusing on local industry production practices, reinforcing even more hygiene and temperature control measures, is provided [44].

These safety standards include initial raw material control; as expected, only high-quality salmon free from parasites and pathogens is permitted to be processed. Cold-smoking parameters must be strictly controlled to prevent contamination as part of good manufacturing practices. Permanent monitoring during vacuum and modified-atmosphere packaging is an additional critical step in preventing anaerobic bacterial growth. As most foodborne pathogens are mesophilic microorganisms, keeping the production temperature below 4 °C is an effective means of controlling some of them. However, *L. monocytogenes* is a psychrophilic microorganism and can proliferate at 4 °C [29]. Environmental production monitoring is crucial for the provision of safe food products; routine swabbing of equipment and facilities is essential to detecting *Listeria* reservoirs. Moreover, permitted preservatives, including organic acid salts and mineral salts, are sometimes employed to reduce microbial risk [44], and some emerging technologies for conservation and bioconservation can be used to reduce and even eliminate potential contaminants, including *L. monocytogenes*, in smoked salmon. These approaches include the use of modified-atmosphere packaging, osmotic pressure, essential oils, cold plasma, antimicrobial peptides (bacteriocins) [28,44].

Despite strict production control of raw material, processing, and distribution, outbreaks associated with consumption of smoked salmon continue to occur, often due to persistent *Listeria* contamination in processing environments [45] (Table 1).

Table 1. Recent *Listeria monocytogenes* outbreaks linked to smoked salmon.

Period	Countries	Total Cases	Dead	Status	Reference
2019 August	Australia		2	Recall	https://foodsmi.com/statistika-i-issledovaniya-/ryba-smertelnogo-kopcheniya , accessed on 5 January 2026
2019–2024	Denmark Germany Italy	17 1 2		Ongoing cluster identified by ECDC/EFSA	European Centre for Disease Prevention and Control, European Food Safety Authority, 2024. Prolonged multi-country outbreak of <i>Listeria monocytogenes</i> ST1607 linked to smoked salmon products—25 April 2024. ISBN 978-92-9498-716-7; doi: 10.2900/061379; Catalog number TQ-02-24-480-EN-N
2020–2024	UK (England and Scotland)	24	4		https://www.foodsafetynews.com/2024/12/reminder-about-smoked-fish-risk-as-listeria-outbreak-continues , accessed on 5 January 2026
2022–2023	Austria, Belgium, Italy, Germany, Netherlands	17	2		https://www.foodbusinessmea.com/smoked-salmon-sparks-listeria-outbreak-across-europe/ , accessed on 5 January 2026
2023 May	Irland			Recall	https://foodsmi.com/statistika-i-issledovaniya-/v-irlandii-otozvan-kopchenyy-losos-iz-za-listeria-monocytogenes , accessed on 5 January 2026
2023 August	Norway			Recall	https://akvakultura.ru/news/9982562 , accessed on 5 January 2026
2024 October	USA			Class I recall	https://www.msn.com/en-us/public-safety-and-emergencies/health-and-safety-alerts/fda-issues-urgent-class-1-recall-for-salmon-sold-at-popular-retail-chain-over-listeria-risk/ar-AA1xXvHF , accessed on 5 January 2026
2025 January	USA			111 cases recalled; FDA warns of serious health risk	https://www.newsweek.com/salmon-recall-update-highest-risk-warning-fda-listeria-monocytogenes-2019477 , accessed on 5 January 2026
2025 June	USA			Investigation ongoing	https://www.foodsafetynews.com/2025/06/washington-company-recalls-salmon-after-tests-show-listeria-contamination , accessed on 5 January 2026
2025 July	Israel			Recall	https://segodnya.co.il/news/minzdrav-soobschaet-v-kopchenoj-rybe-obnaruzhena-opasnaja-bakterija , accessed on 5 January 2026

Based on available information from European health agencies and food-safety reports.

6. Use of Bacteriocins in Biopreservation of Smoked Salmon

Since their discovery, bacteriocins have been suggested as tools for increasing food safety and reducing/eliminating of food spoilage and foodborne pathogens [6]. Specifically, bacteriocins have received scientific attention as attractive tools for the biopreservation of smoked salmon [45]. Smoked salmon offers ideal environmental conditions for the bacterial growth—it has relatively high moisture content, moderate salt levels, and chilled storage conditions that prevent mesophilic bacterial spoilage but are excellent for the psychrotolerant *L. monocytogenes*. As it is considered a luxury food commodity, smoked salmon has received criticism for its content of chemical preservatives, with the potential application of healthier biopreservatives evaluated positively by consumers. This scientific and industrial challenge served as the initial point for evaluating alternatives for the conservation of smoked salmon, including the possibility of applying different natural antimicrobial strategies, including bacteriocins, particularly those produced by LABs, which are one of the most promising options (Figure 2).

Biopreservation strategies using bacteriocins in smoked salmon production

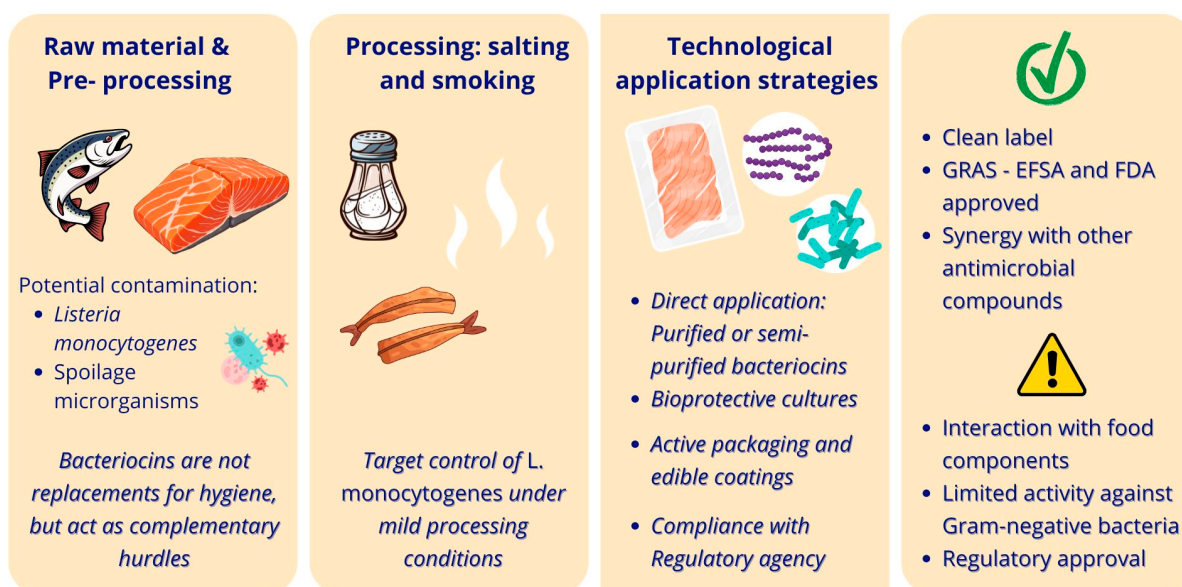


Figure 2. Application of bacteriocins along the salmon production chain. Raw material and pre-processing, indicating the risk of microbial contamination; Processing steps where bacteriocins may be applied to improve microbial control; technological application strategies; and main advantages and points of attention.

According to the broadly accepted definition, bacteriocins are antimicrobial peptides that inhibit closely related bacteria. Since *L. monocytogenes*, a principle spoilage organism, was targeted by developing new preservation alternatives, bacteriocins from LABs have been studied as promising alternatives [8]. Nisin, the first LAB-produced bacteriocin described in literature and industrially produced under commercial name Nisaplin, was widely evaluated as biopreservative in the preservation of seafood, including smoked salmon [45]. Considering that nisin is able to interfere with integrity of the bacterial cell membranes, it is a good candidate for effectively combating Gram-positive organisms, including *L. monocytogenes*, which is a major concern in ready-to-eat fish products [29,45]. When applied to smoked salmon (whether directly, integrated into brine during processing, or incorporated on packaging materials) nisin can effectively reduce the growth of *L. monocytogenes* during refrigerated storage. Beyond nisin, other bacteriocins such as pediocin PA 1, sakacin, enterocins, piscicollin, and carnobacteriocins (variations in the

name can be observed in the literature) have shown strong potential for smoked salmon preservation (Figure 2).

Some experimental studies showed that nisin and pediocin PA-1, both of which are commercially available and permitted by the EFSA and FDA (under the commercial names Nisaplin and Microgart) for application in food biopreservation, can be effectively applied to control *L. monocytogenes*. Zuckerman and Avraham [46] applied a combination of nisin and pediocin PA-1 and reduced the total aerobic bacterial population (initial load: 4.7 log) in fresh chilled salmon by 2 log, which increased the shelf-life by 3–4 days when stored at 6 °C. They found that the application of a combination of nisin and pediocin PA-1 effectively reduced the growth of *L. monocytogenes* added to salmon filets, increasing the estimated shelf life of thawed salmon from 5 to 10 d when stored at 6 °C. Interestingly, they observed that the addition of the nisin and pediocin PA-1 combination did not influence the surface pH value or color of the fish [46].

Other studies have also examined genetic differences in *L. monocytogenes*, and Chen et al. [47] designed experiments in which different serotypes of *L. monocytogenes* were used as model microorganisms. They [47] evaluated influence of nisin concentration (0, 25, or 250 ppm) and storage temperature (4 or 7 °C) on the inhibition of *L. monocytogenes* (1/2a, 1/2b and 4b serotypes) inoculated into salmon at $\sim 10^2$ CFU/g, a typical contamination level for 30 days. Authors showed that the effectiveness of nisin was dose-dependent and presented similar results when applied at 4 or 7 °C. Moreover, it was found that the serotype 1/2b strain was more sensitive to nisin than the serotype 1/2a and 4b strains in samples incubated at 7 °C or treated with 25 ppm of nisin [47].

NaCl application is one of the oldest and most common ways to reduce water activity and prevent bacterial growth (Figure 2). Smoking and salting is a traditional approach to controlling spoilage and the growth of pathogenic bacterial species in salmon; however, increasing the levels of NaCl in preserved salmon is not a solution. It is recognized that excess dietary intake of NaCl is associated with serious health complications. Heir et al. [48] explored combinations of different strategies for the control of *L. monocytogenes* in smoked salmon: nisin and P100 bacteriophages (Phageguard L, PGL) and fermentates (Verdad N6, P-NDV) in standard (with NaCl) and sodium-reduced (NaCl partially replaced with KCl) cold-smoked salmon. The application of 1 ppm of nisin in the preservation of cold-smoked salmon and PGL (5×10^7 Plaque Forming Units (PFU)/cm²) applied individually yielded reductions in *L. monocytogenes* (up to 0.7 log) compared to untreated samples. It is important to note that in all experiments, the initial contamination with *L. monocytogenes* was controlled at 4.0 log CFU/g, and the combination of nisin and PGL showed a synergistic effect of inhibiting *L. monocytogenes* in these experiments. When fermentates were applied for the control of *L. monocytogenes* in cold-smoked salmon, a positive effect was observed, but it was not eradicated. Moreover, the lowest levels of *L. monocytogenes* were recorded when combinations of nisin and PGL were applied during the preservation process and preservative fermentates were included in an experimental set-up at 4 °C, while enhanced growth was observed during storage at a harmful temperature of 8 °C [48]. Moreover, the authors reported that when compared to standard industry-processed and sodium-replaced cold-smoked salmon (combination of nisin, PGL, and containing fermentates), their method achieved as much as 1.7 log reductions in *L. monocytogenes* for a storage period of 34 days. It is important to point out the specific inactivation of *Listeria*'s effects in this experimental set-up, since no differences in total aerobic plate counts were observed between treated and non-treated standard and sodium-reduced cold-smoked salmon at the end of storage. In conclusion, the authors suggested that similarly robust reductions in *L. monocytogenes* counts can be achieved in both standard and sodium-replaced cold-smoked salmon using the biopreservation strategy of combined nisin, PGL and fermentates [48].

Duffes et al. [49] evaluated possible applications of bacteriocins produced by *Carnobacterium piscicola* V1 and *Carnobacterium divergens* V41, arguing that both bacteriocins' producers were isolated from smoked fish and that the bacteriocins themselves presented very strong anti-*Listeria* activity in preliminary experiments. In an experimental set-up for the evaluation of activity *in silico*, the authors applied crude bacteriocins (cell-free supernatant (CFS) containing bacteriocins) on sterile and commercial vacuum-packed cold-smoked salmon under experimental conditions of 4 °C and 8 °C. The bacteriocin produced by *C. piscicola* V1 exhibited bactericidal effects against *L. monocytogenes* at both temperatures tested, whereas the bacteriocin produced by *C. divergens* V41 had a bacteriostatic effect on *L. monocytogenes*. The experiments were performed with an initial load of *L. monocytogenes* of 4.0 log CFU/g. The bacteriocins produced by *C. piscicola* SF668 delayed the growth of *L. monocytogenes* at 8 °C and had a bacteriostatic effect at 4 °C. As a control, a non-bacteriocin-producing *C. piscicola* strain was used; as anticipated, it showed no inhibitory effect on *L. monocytogenes*. Moreover, while bacteriocins from *C. piscicola* were bactericidal at both evaluated temperatures (4 °C and 8 °C), *L. monocytogenes* growth was only delayed after the application of bacteriocins produced by *C. divergens* V41 [49]. Nisin was also investigated as control, and it delayed *L. monocytogenes* growth at 8 °C and was bacteriostatic at 4 °C. In conclusion, the authors emphasized that *L. monocytogenes* growth could be prevented on vacuum-packed cold-smoked salmon by bacteriocins produced by *C. piscicola* V41 or *C. divergens* V41 at chilled temperatures [49].

As previously shown by Duffes et al. [49], bacteriocins can be an effective solution for controlling *L. monocytogenes* in cold-smoked salmon. The next challenge was to explore bacteriocin production *in silico* and determine the bioprotective properties of the bacteriocin producers [50]. In the experimental set-up, the bacteriocin producer *C. divergens* V41 was incorporated into a polypropylene film and evaluated for the inhibition of *L. monocytogenes* growth in culture media and in cold-smoked salmon at refrigerated temperatures. When its inhibitory properties were evaluated on semi-solid Brain Heart Infusion (BHI) agar, the bioprotective plastic membrane resulted in a 3-log reduction in the *L. monocytogenes* count compared to the control in an experiment conducted over 14 days at an aerobic incubation temperature of 8 °C. In the experiment, the initial load of *L. monocytogenes* was around 4.0 log. When the experiment was conducted with vacuum-packed cold-smoked salmon, *L. monocytogenes* growth was inhibited by the bioprotective plastic membrane for 7 days when stored at 4 °C and for 21 days when stored at 8 °C. Nguyen et al. [50] assessed the stability and viability of *C. divergens* incorporated into the protective packaging and estimated that even after 42 days at 4 °C, anti-*Listeria* activity was 2 log when tested on BHI agar compared to the control. Although this research is still in its early stages, the referenced study highlights the potential for developing bio-protective plastic membranes that can be used to control pathogenic bacteria in food products, with promising prospects for industrial application [50].

In exploring alternatives for bioconservation, the anti-*Listeria* property of bacteriocins produced by *Latilactobacillus curvatus* CWBI-B28 was investigated in cold-smoked salmon during storage at 4 °C by Ghalfi et al. [51]. These authors experimentally evaluated three bacteriocin-based strategies—producing bacteriocin *in situ*, spraying with partially purified bacteriocin, and packaging in bacteriocin-coated plastic film. Moreover, they [51] suggested an experimental procedure that optimized bacteriocin adsorption to the cell surface of the producer by adjusting the pH. Notably, all their experiments demonstrated inactivation of *L. monocytogenes* in cold-smoked salmon, although the degree of efficacy varied among set-ups. The inhibitory profile of *L. monocytogenes* was similar in samples treated with either partially purified bacteriocins or bacteriocins produced *in situ*. To some extent, this result is surprising, since the experiments were performed at 4 °C and

at this temperature does not support growth of *Ltb. curvatus*, or any LABs [52]. Most had probably already produced bacteriocins, and those absorbed to the cell surface were actually desorbed and responsible for the antimicrobial properties. However, this hypothesis merits additional investigation. In both cases described by Ghalfi et al. [51], the *Listeria* count was reduced to below the detectable limit of 0.7 log CFU/cm² within the first week. However, some recovery of *L. monocytogenes* was observed after 14 days and 0.95-log and 1.3-log increases were recorded with either partially purified bacteriocin or in situ bacteriocin production, respectively. In the experiment where bioactive packaging film was applied, a slower *L. monocytogenes* inactivation was recorded, however, preventing any subsequent increase in the CFU throughout 22 days of storage at 4 °C. Overall, the innovative application of cell-adsorbed bacteriocins presented the most promising results, as it led to complete inactivation of the pathogen within 3 days, and no recovery of *L. monocytogenes* was recorded for up to 22 days [51].

Bacteriocins produced by *Lactiplantibacillus pentosus* 39 were shown to be effective against *Aeromonas hydrophila* ATCC 14715 and *L. monocytogenes* ATCC 19117 when added to fresh salmon filets at refrigeration temperatures and under simulated cold-chain break conditions [53]. In an experimental set-up, an *Lpb. pentosus* 39 protective culture and its bacteriocins effectively reduced *A. hydrophila* ATCC 14715 counts compared with the control (0.7 log CFU/g reductions), while for *L. monocytogenes* ATCC 19117, the reduction was from 3.6 to 1.3 log CFU/g. When the temperature increased to 30 °C for 12 h, the metabolite activity of *Lpb. pentosus* 39 activated, including a consequent increase in bacteriocin production. This resulted in a greater reduction in both pathogens compared with samples stored at 4 °C throughout the experiment—a 2.8 log CFU/g reduction for *A. hydrophila* ATCC 14715 and a 5.8 log CFU/g reduction for *L. monocytogenes* ATCC 19117. However, when experiments were performed with only the studied bacteriocin and without *Lpb. pentosus* 39, a less effective decrease in the counts of both pathogens was observed [53].

In a similar set of experiments, Tome et al. [54] explored the bioprotective properties of *Enterococcus faecium* ET05, *Ltb. curvatus* ET06, *Ltb. curvatus* ET30, *Lactobacillus delbrueckii* ET32, and *Pediococcus acidilactici* ET34, which they used to produce bacteriocins against *Listeria innocua* 2030c in vitro under conditions simulating cold-smoked salmon processing and storage at 5 °C. Tome et al. [54] compared biopreservative properties of the above-mentioned five strains and identified *E. faecium* ET05 as the most effective at controlling *L. innocua*. Other evaluated strains, *Ltb. curvatus* ET30 and *Lab. delbrueckii* ET32, also showed good biopreservation potential; however, *Ltb. curvatus* ET06 and *P. acidilactici* ET34 had only a bacteriostatic effect on *L. innocua* in in vitro experiments [54].

Katla et al. [55] explored the application of sakacin P and nisin as individual conservation agents and/or one of two *Latilactobacillus sakei* strains evaluated in this study. One is a producer of sakacin P, and the other served as a control in a culture without bacteriocin production. The experiments were conducted over a period of four weeks at a temperature of 10 °C. In the experiment, both bacteriocins (sakacin P and nisin) presented an initial inhibiting effect on growth of *L. monocytogenes* in smoked salmon. However, supplementation with live cultures of *Ltb. Sakei*, which produces sakacin P, and not a bacteriocin had a clear bacteriostatic effect on *L. monocytogenes* during the investigated storage period. Notably, the addition of the *Ltb. sakei* strain that produces sakacin P, together with sakacin P itself, to vacuum-packed cold-smoked salmon resulted in a pronounced bactericidal effect against *L. monocytogenes* [55].

The effect of *C. divergens* M35, the producer of divercin M35, and *C. divergens* ATCC 35677, which does not produce a bacteriocin, and purified divercin M35 or supernatants of *C. divergens* M35 against *L. monocytogenes* (up to 10³ CFU/g) was explored in a smoked salmon preservation strategy [56]. The experiments were conducted at 4 °C for up to

28 days. As *C. divergens* can produce biogenic amines, the authors not only evaluated the inhibition of *L. monocytogenes* but also considered the subsequent formation of biogenic amines and changes in the organoleptic properties of smoked salmon, including texture, color, and odor. An experiment with a live *C. diverganece* M35 culture showed a reduction of 2.6 log CFU/g for *L. monocytogenes* in the first 10 days of storage. However, the application of purified divercin M35 at 50 mg/g of bacteriocin-containing CFS resulted in a reduction of 1 log CFU/g at the beginning of storage. Moreover, the anti-*Listeria* activity of the CFS lasted for 15 days compared to 3 days for purified divercin M35. It is relevant to mention that the authors noted that color and texture were affected only slightly in samples containing *C. divergens* M35 compared to un-inoculated samples. Moreover, production of biogenic amines, particularly tyramine, remained below the maximum acceptable level in fish [56].

The bacteriocin EFL4, produced by *E. faecalis* L04 [57], was evaluated for its ability to inhibit the growth of *L. monocytogenes* and other fish-spoilage bacteria and food-borne pathogens, including *Staphylococcus aureus*, *E. coli*, *Shewanella putrefaciens*, and *Pseudomonas fluorescens*. The beneficial properties of bacteriocin EFL4 in the preservation of smoked salmon were validated at 4 °C, where microbiological and physicochemical properties, including organoleptic evaluations, were taken into account by the authors. Based on the organoleptic evaluation results, only 0.64 µg/mL of bacteriocin EFL4 was sufficient to reduce the total viable count and total volatile basic nitrogen and to maintain the quality of smoked salmon for 8 days of storage [57].

A bacteriocin produced by *C. piscicola* L103 was shown to be effective against *L. monocytogenes* in an experiment reported by Schöbitz et al. [58] in vacuum-packaged salmon. The authors supplemented salmon filets with bacteriocin at 200 Arbitrary Units (AU)/mL and 800 AU/mL, inoculated them with 8.0×10^1 CFU/cm² of *L. monocytogenes*, and stored them at 4 °C for 15 days. Both experimental concentrations of bacteriocins had a bacteriostatic effect on *L. monocytogenes* when inoculated in salmon, with differences of almost 3 logs between the control and experimental set-ups (6.0×10^3 cfu/cm² for the bacteriocin treated salmon and 1.0×10^6 CFU/cm² for the control after 15 days of storage) [58].

Researchers have also investigated the development of multi-functional packaging materials with preservation properties. In the study by Li et al. [59], nanofiber films with antimicrobial and antioxidant activity containing PCL/lecithin/bacteriocin CAMT6, produced by *Enterococcus durans* YQ-6, were prepared using the emulsion electrostatic spinning approach and used as a packaging material for smoked salmon, achieving effective control of *L. monocytogenes* [59].

In a similar work, piscicolin CM22, produced by *Carnobacterium maltaromaticum* CM22, was incorporated into two types of edible coatings—chitosan-based and fish gelatin-based [60]. The efficacy of the edible bacteriocin-containing coatings was evaluated through shelf-life and challenge tests with *L. monocytogenes* in raw and smoked fish products. The results showed that incorporating piscicolin CM22 provided additional bioprotective properties not only in smoked salmon but also in fresh salmon and tuna. The designed coating with piscicolin CM22 was able to reduce *L. monocytogenes* counts by up to 4 log CFU/g in raw and smoked refrigerated fish samples for 15 days [60].

One of the greatest advantages of applying bacteriocins in smoked salmon preservation is that they align with consumer demand for “clean label” foods. Several research projects also highlight that bacteriocins do not interfere with flavor or the other organoleptic properties of food [6]; thus, these natural antimicrobials can provide a way to maintain safety and shelf life without compromising product specificity. Moreover, bacteriocins are generally recognized as safe, and nisin and pediocin PA-1 are industrially produced

and marked and permitted by the EFSA and FDA. They degrade naturally and do not significantly alter the sensory qualities of smoked salmon [37].

However, the use and effectiveness of bacteriocins can be associated with some technological challenges (Figure 2). As they are proteinaceous by nature, their antimicrobial activity can be influenced by the composition of the salmon matrix, including the fat content, salt concentration, and the presence of smoke compounds or other permitted additives. Bacteriocins, including nisin, have a strong affiliation for lipid II, using it as receptor for initial recognition and subsequent killing of target cells [8]. Because bacteriocins can bind to food components, especially those rich in fat, through nonspecific interactions with lipids, their availability to act on target bacteria may be reduced [37]. Additionally, LAB bacteriocins, which have received the most attention as candidates for the biopreservation of smoked salmon, are most effective against other Gram-positive organisms [8,16]. However, *L. monocytogenes* (Gram-positive species) is not the only bacterium related to smoked salmon spoilage. Other microbial species, including several Gram-negative bacteria, may be present in fish products [61], meaning that preservation strategies must be combined with other approaches, such as modified-atmosphere packaging, low storage temperatures, and mild organic acids, to achieve broad protection and effective biopreservation. Moreover, there is also ongoing discussion about the potential for resistance development, though this risk appears lower than with traditional antibiotics [62].

It is clear that the application of bacteriocins is not a panacea that resolves all spoilage problems in smoked salmon production. However, the integration of bacteriocins into smoked salmon preservation strategies is a significant step toward safer, clean-label, and more natural seafood products. There is still room to explore novel technologies and researchers' hypotheses as to whether bacteriocins can be applied directly, as part of active packaging, or via in situ production by bioprotective cultures. Future research may even consider the use of probiotics in smoked salmon, through which biopreservation and the provision of beneficial microbial cultures can be combined. It is clear that bacteriocins offer an effective means of controlling spoilage and pathogenic bacteria in food products; the challenge remaining is for the researchers to provide appropriate technological solutions for effective bioconservation.

7. Postbiotics to Reduce *Listeria monocytogenes*

In last decade, the concept of postbiotics has attracted scientific attention [63]. Defined by the International Scientific Association for Probiotics and Prebiotics (ISAPP) in 2021 as “a preparation of inanimate microorganisms and/or their components that confers a health benefit on the host” [64], the term is associated with some uncertainty, with some misinterpretations in the literature. However, the scientific community agrees that postbiotics are unviable cell preparations in which previously produced metabolites and the components of the dead cells can offer beneficial effects [65]. Despite industry–scientific consensus on the definition, postbiotics have been proposed as a promising natural strategy for enhancing the microbial safety of fermented food products and may play a role in the control of *L. monocytogenes*. Metabolites with biopreservation properties such as bacteriocins and organic acids have been suggested and applied as effective tools for control of *L. monocytogenes* in salmon; thus, if cell preparations containing these biopreservatives do not affect the quality of the final product or compromise its safety, then non-purified bacteriocins may be an even more attractive alternative for ensuring the microbiological quality of smoked salmon. This justifies scientific and industry interest in alternative or complementary approaches, and postbiotics (non-viable microbial metabolites or components) may be such an alternative for biopreservation. In this context, postbiotic preparations based on LABs can provide not only bacteriocins and organic acids but a variety of enzymes and

bioactive peptides [66]. As part of such postbiotic preparations, bacteriocins can contribute to food safety through biocontrol applications. Their role in reducing infection risk and supporting host health makes them a promising tool in functional foods and therapeutic strategies as well.

It is important to emphasize that these bioactive compounds retain their beneficial effects and antimicrobial activity without the need to introduce live microorganisms into the product. This can impact safety issues and simplify regulatory considerations and even avoids concerns about microbial competition or survival during storage and the production of some other undesirable microbial metabolites, such as biogenic amines [67].

8. Benefits of Using Bacteriocins

Bacteriocins can provide different microbial benefits compared to other traditional conservation methods. One of their principle benefits is the fact that bacteriocins align with trends of bioconservation, reduce the addition of synthetic preservatives [6,8], and align with the United Nations' directive for sustainable food production. Other major benefits are their high specificity for and efficacy against key pathogens identified in the production of smoked salmon, especially the psychrotolerant *L. monocytogenes*. *L. monocytogenes* is also known to be tolerant to salt, smoke, and refrigeration [28]. However, bacteriocins such as nisin, pediocin, carnocins, and sakacin have proven effective against *L. monocytogenes* and can contribute to meaningful reductions/eliminations even under refrigeration.

It is important to note that bacteriocins have a minimal impact on sensory quality [16] and fit the demand for clean-label and natural preservation strategies; unlike synthetic preservatives such as nitrites or sorbates, bacteriocins are naturally produced polypeptides. Moreover, they can be applied in combination with other traditional preservation processes, and synergetic interactions have already been reported [10,68]. The effect of bacteriocins is not compromised by refrigeration, vacuum packaging, modified-atmosphere packaging, or mild salting [16] (Figure 2).

Taken together, bacteriocins provide a rare combination of efficacy, natural origin, sensory neutrality, and technological flexibility. That is why they are increasingly viewed as one of the most promising tools for improving the safety and shelf life of smoked salmon without compromising its premium quality.

9. Some Limitations and Further Perspectives

Bacteriocins offer several advantages and benefits for the biopreservation of not only salmon but also several other food products. However, some drawbacks and limitations need to be taken into consideration regarding technological processes. Bacteriocins are part of a complex preservation process and not a one-strategy approach. Perhaps one of the most important limitations to note, as previously mentioned, is that bacteriocins of LABs mainly target Gram-positive bacteria [16,18]. Some reports have pointed out that when applied in higher doses, specific bacteriocins from LABs can even present some unorthodox activity and an extended spectrum of activity [14]. The specificity of bacteriocins means that they can be highly effective against *L. monocytogenes*; however, they have little or even no effect against Gram-negative spoilage organisms commonly found in seafood. Moreover, *Pseudomonas*, *Shewanella*, *Vibrio*, and other psychrotolerant bacteria that are associated with off-odors and texture degradation cannot be effectively controlled by LAB bacteriocins. All this clearly indicates that bacteriocins alone cannot fully prevent spoilage and provide complete safety in smoked salmon (Figure 2).

Complex food matrices present an additional problem, as they can have a negative impact on the bioavailability of bacteriocins. Smoked salmon is a fish product and thus contains fat and proteins, and salting and smoking are part of its preparation [41]. Interactions

between bacteriocins and the food matrix and additives can occur and compromise the viability of the bacteriocins. The distribution of bacteriocins is another potential obstacle, as an uneven distribution can compromise their efficacy in controlling *L. monocytogenes*. In addition, the fact that *L. monocytogenes* can form biofilms should not be neglected [28].

The development of resistance must be considered when designing long-term strategies for conservation and biopreservation. Although bacteriocin resistance tends to be less common and less stable than antibiotic resistance, repeated exposure can select for strains with reduced sensitivity. This is particularly relevant in processing environments where *Listeria* can persist over long periods. While the risk is not considered high, it is still monitored by producers and regulators [62].

Simple matters such as regulations and cost should also be evaluated. Currently, only nisin and pediocin PA-1 are commercially produced and permitted for industrial applications [6]. Although there is laboratory-scale evidence that other bacteriocins can be effective in controlling *L. monocytogenes*, their industrial application may face global or regional restrictions, which can limit their use in commercial smoked salmon production and commercialization. Regulations need to clearly state how bacteriocins will be applied, whether as postbiotics, crude extracts, or semi-purified; and whether they are produced by heterologous expression or native microbial cultures. Cost-effective production strategies need to be designed, and the final added cost of applying bacteriocins as a biopreservative strategy should be compared to those of traditional preservation methods like salting, smoking, and using modified-atmosphere packaging.

Taken together, these limitations do not undermine the value of bacteriocins, but they do explain why they are most effective when combined with other preservation strategies. Bacteriocins offer good protection against *Listeria*, but they are not a complete preservation system on their own.

10. Conclusions

Smoked salmon is a highly valued ready-to-eat gastronomic product; however, it may carry *L. monocytogenes*, a foodborne pathogen that is hazardous to health, particularly for vulnerable consumers. The nature of *L. monocytogenes* makes it highly resistant and able to persist in processing environments, survive refrigeration, and form biofilms, posing significant food safety challenges for producers and consumers. Can food products be free of *L. monocytogenes*? We need to act according to regulations and provide food products that meet the requirements for spoilage and foodborne pathogens, including *L. monocytogenes*. In this review, we examined the prevalence and behavior of *L. monocytogenes* in smoked salmon, emphasizing factors that enable its growth during storage. A major focus was the use of LAB bacteriocins as realistic strategy for controlling *L. monocytogenes* and as natural biopreservation tools. Some bacteriocins, such as nisin, pediocin, carnocins, piscicocins, and enterocins, demonstrate strong anti-*Listeria* activity and can be applied directly, incorporated into packaging, or delivered through protective cultures or even as postbiotics. With this review, our intention was not to provide a list of solutions but to spark creative thinking and scientific interest in finding effective biopreservatives, keeping in mind limitations, and evaluating potential synergistic combinations with other preservatives. Overall, bacteriocins offer a promising strategy to enhance the microbial safety of smoked salmon while meeting consumer demands for clean-label preservation methods. We now need to find an appropriate strategy for applying them.

Author Contributions: Conceptualization, S.D.T. and I.V.I.; literature review, T.M.W., E.M.F.L., D.R., A.E., B.M., K.A.L., V.N.K., A.K., A.S.D., Y.A.K., O.V.M., M.M., M.V.-V., I.V.I., and S.D.T.; investigation, T.M.W., E.M.F.L., D.R., A.E., B.M., K.A.L., V.N.K., A.K., A.S.D., Y.A.K., O.V.M., M.M., M.V.-V., I.V.I., and S.D.T.; writing—original draft preparation, T.M.W. and S.D.T.; writing—review and editing, E.M.F.L., O.V.M., M.M., M.V.-V., I.V.I., and S.D.T.; visualization, T.M.W., E.M.F.L., and S.D.T.; supervision, S.D.T.; project administration, S.D.T.; funding acquisition, D.R., A.E., B.M., V.N.K., and S.D.T. All authors have read and agreed to the published version of the manuscript.

Funding: Sao Paulo Research Foundation (FAPESP) (grants 2023/05394-9; 2024/01721-8; 2024/13311-9), São Paulo, SP, Brazil; Support of the Administration of the Volgograd Region for funding research activities under the grant of the Administration of the Volgograd Region, pursuant to Agreement No. 2 dated 12 December 2024, with Volgograd State Technical University, Russian Federation; Support by the grant of the Russian Science Foundation No. 23-76-30006, Russian Federation; Centre for Research and Development in Agrifood Systems and Sustainability, Fundação para a Ciência e Tecnologia, Portugal for funding—UID/05937/2025 (DOI:10.54499/UID/05937/2025).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: This research was based on a literature review, and no new data was generated.

Acknowledgments: During the preparation of this manuscript, the authors used AI tools (ChatGPT (model GPT-4) and Grammarly 2.0) for improving the grammar and style of some sentences but not for generating content. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the current article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Adams, S.H.; Anthony, J.C.; Carvajal, R.; Chae, L.; Khoo, C.S.H.; Latulippe, M.E.; Matusheski, N.V.; McClung, H.L.; Rozga, M.; Schmid, C.H.; et al. Perspective: Guiding Principles for the Implementation of Personalized Nutrition Approaches That Benefit Health and Function. *Adv. Nutr.* **2020**, *11*, 25–34. [\[CrossRef\]](#) [\[PubMed\]](#)
- Mozaffarian, D.; Blanck, H.M.; Garfield, K.M.; Wassung, A.; Petersen, R. A Food is Medicine approach to achieve nutrition security and improve health. *Nat. Med.* **2022**, *28*, 2238–2240. [\[CrossRef\]](#) [\[PubMed\]](#)
- González-Palacios, S.; Fonollá, J. Advances in Nutrient-Rich Foods for a Healthy Diet. *Foods* **2023**, *12*, 2946. [\[CrossRef\]](#) [\[PubMed\]](#)
- Todorov, S.D.; Kajikawa, H.S.; Penna, A.L.B.; Chikindas, M.L.; Pot, B. Announcement: Yakult International Symposia on Beneficial Microbes—Fundamental Science and Innovative Applications, Sao Paulo, SP, Brazil, 27–28 March 2025. *Probiotics Antimicrob. Proteins* **2024**, *16*, 1499–1500. [\[CrossRef\]](#)
- Vijayaganapathi, A.; Mohanasrinivasan, V. A Review of Next-Generation Probiotics—As a Gateway to Biotherapeutics. *Probiotics Antimicrob. Proteins* **2025**, *17*, 1985–1997. [\[CrossRef\]](#)
- Field, D.; de Ullivarri, M.F.; Ross, R.P.; Hill, C. After a century of nisin research—Where are we now? *FEMS Microbiol. Rev.* **2023**, *47*, fuad023. [\[CrossRef\]](#)
- Todorov, S.D.; Popov, I.; Weeks, R.; Chikindas, M.L. Use of Bacteriocins and Bacteriocinogenic Beneficial Organisms in Food Products: Benefits, Challenges, Concerns. *Foods* **2022**, *11*, 3145. [\[CrossRef\]](#)
- Choi, G.H.; Holzapfel, W.H.; Todorov, S.D. Diversity of the bacteriocins, their classification and potential applications in combat of antibiotic resistant and clinically relevant pathogens. *Crit. Rev. Microbiol.* **2023**, *49*, 578–597. [\[CrossRef\]](#)
- Chi, H.; Holo, H. Synergistic Antimicrobial Activity Between the Broad Spectrum Bacteriocin Garvicin KS and Nisin, Farnesol and Polymyxin B Against Gram-Positive and Gram-Negative Bacteria. *Curr. Microbiol.* **2018**, *75*, 272–277. [\[CrossRef\]](#)
- Bucheli, J.E.V.; Fugaban, J.I.L.; Holzapfel, W.H.; Todorov, S.D. Combined Action of Antibiotics and Bacteriocins against Vancomycin-Resistant Enterococci. *Microorganisms* **2022**, *10*, 1423. [\[CrossRef\]](#)
- Zheng, Y.; Du, Y.; Qiu, Z.; Liu, Z.; Qiao, J.; Li, Y.; Caiyin, Q. Nisin Variants Generated by Protein Engineering and Their Properties. *Bioengineering* **2022**, *9*, 251. [\[CrossRef\]](#)
- Field, D.; Cotter, P.D.; Ross, R.P.; Hill, C. Bioengineering of the model lantibiotic nisin. *Bioengineered* **2015**, *6*, 187–192. [\[CrossRef\]](#) [\[PubMed\]](#)

13. Anton, R.; Barlow, S.; Dimitrios, B.; Castle, L.; Crebelli, R.; Dekant, W.; Engel, K.H.; Forsythe, S.; Grunow, W.; Heinonen, M.; et al. Opinion of the Scientific Panel on food additives, flavourings, processing aids and materials in contact with food (AFC) related to The use of nisin (E 234) as a food additive. *EFSA J.* **2006**, *4*, 314. [\[CrossRef\]](#)
14. Jozala, A.F.; Lopes, A.M.; Mazzola, P.G.; Magalhães, P.O.; Vessoni Penna, T.C.; Pessoa, A., Jr. Liquid–liquid extraction of commercial and biosynthesized nisin by aqueous two-phase micellar systems. *Enzyme Microb. Technol.* **2008**, *42*, 107–112. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Karakas-Sen, A.; Narbad, A. Heterologous expression and purification of NisA, the precursor peptide of lantibiotic nisin from *Lactococcus lactis*. *Acta. Biol. Hung.* **2012**, *63*, 301–310. [\[CrossRef\]](#)
16. Chikindas, M.L.; Weeks, R.; Drider, D.; Chistyakov, V.A.; Dicks, L.M. Functions and emerging applications of bacteriocins. *Curr. Opin. Biotechnol.* **2018**, *49*, 23–28. [\[CrossRef\]](#)
17. Jack, R.W.; Tagg, J.R.; Ray, B. Bacteriocins of Gram-positive bacteria. *Microbiol. Rev.* **1995**, *59*, 171–200. [\[CrossRef\]](#)
18. Todorov, S.D.; de Melo Franco, B.D.G.; Tagg, J.R. Bacteriocins of Gram-positive bacteria having activity spectra extending beyond closely-related species. *Benef. Microbes* **2019**, *10*, 315–328. [\[CrossRef\]](#)
19. Tagg, J.R.; Dajani, A.S.; Wannamaker, L.W. Bacteriocins of Gram-positive bacteria. *Bacteriol. Rev.* **1976**, *40*, 722–756. [\[CrossRef\]](#)
20. Sugrue, I.; Ross, R.P.; Hill, C. Bacteriocin diversity, function, discovery and application as antimicrobials. *Nat. Rev. Microbiol.* **2024**, *22*, 556–571. [\[CrossRef\]](#)
21. Burgos, M.J.G.; Pulido, R.P.; Aguayo, M.D.C.L.; Gálvez, A.; Lucas, R. The Cyclic Antibacterial Peptide Enterocin AS-48: Isolation, Mode of Action, and Possible Food Applications. *Int. J. Mol. Sci.* **2014**, *15*, 22706–22727. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Aguirre-Garcia, Y.L.; Nery-Flores, S.D.; Campos-Muquiza, L.G.; Flores-Gallegos, A.C.; Palomo-Ligas, L.; Ascacio-Valdés, J.A.; Sepúlveda-Torres, L.; Rodríguez-Herrera, R. Lactic Acid Fermentation in the Food Industry and Bio-Preservation of Food. *Fermentation* **2024**, *10*, 168. [\[CrossRef\]](#)
23. Joerger, M.C.; Klaenhammer, T.R. Characterization and purification of helveticin J and evidence for a chromosomally determined bacteriocin produced by *Lactobacillus helveticus* 481. *J. Bacteriol.* **1986**, *167*, 439–446. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Castrejón-Jiménez, N.S.; Castrejón-Jiménez, I.A.; Rojas-Campos, T.O.; Chavarria-Hernández, N.; García-Pérez, B.E.; Hernández-González, J.C. Classification of Bacteriocins from Lactic Acid Bacteria and Their Mode of Action. In *Antimicrobial Peptides from Lactic Acid Bacteria*; Ray, S., Kumar, P., Mandal, M., Eds.; Springer: Singapore, 2024; pp. 33–65. [\[CrossRef\]](#)
25. Rani, A.; Saini, K.C.; Bast, F.; Varjani, S.; Mehariya, S.; Bhatia, S.K.; Sharma, N.; Funk, C. A Review on Microbial Products and Their Perspective Application as Antimicrobial Agents. *Biomolecules* **2021**, *11*, 1860. [\[CrossRef\]](#)
26. Bahrami, S.; Andishmand, H.; Pilevar, Z.; Hashempour-baltork, F.; Torbati, M.; Dadgarnejad, M.; Rastegar, H.; Mohammadi, S.A.; Azadmard-Damirchi, S. Innovative perspectives on bacteriocins: Advances in classification, synthesis, mode of action, and food industry applications. *J. Appl. Microbiol.* **2024**, *135*, 1x274. [\[CrossRef\]](#)
27. Bédard, F.; Hammami, R.; Zirah, S.; Rebuffat, S.; Fliss, I.; Biron, E. Synthesis, antimicrobial activity and conformational analysis of the class IIa bacteriocin pediocin PA-1 and analogs thereof. *Sci. Rep.* **2018**, *8*, 9029. [\[CrossRef\]](#)
28. d'Ovidio, L.; de Oliveira, D.P.; Ivanova, I.V.; Vaz-Velho, M.; Franco, B.D.G.M.; Todorov, S.D. *Listeria Monocytogenes*—Can We Reduce or Eliminate It from Food Commodities? *Mol. Nutr. Food Res.* **2026**, *70*, e70329. [\[CrossRef\]](#)
29. Gandhi, M.; Chikindas, M.L. *Listeria*: A foodborne pathogen that knows how to survive. *Int. J. Food Microbiol.* **2007**, *113*, 1–15. [\[CrossRef\]](#)
30. Orsi, R.H.; Wiedmann, M. Characteristics and distribution of *Listeria* spp., including *Listeria* species newly described since 2009. *Appl. Microbiol. Biotechnol.* **2016**, *100*, 5273–5287. [\[CrossRef\]](#)
31. FAO; WHO. *Risk Assessment of Listeria monocytogenes in Ready-to-Eat foods: Technical Report*; World Health Organization and Food and Agriculture Organization of the United Nations: Geneva, Switzerland, 2004; pp. 1–269.
32. Codex Alimentarius Commission. *Guidelines on the Application of General Principles of Food Hygiene to the Control of Listeria monocytogenes in Foods-CAC/GL 61-2007*; Codex Alimentarius Commission: Rome, Italy, 2009.
33. Center for Food Safety and Applied Nutrition. *Control of Listeria monocytogenes in Ready-to-Eat Foods: Guidance for Industry (Draft Guidance)*; US Food and Drug Authority (FDA): Rockville, MD, USA, 2017.
34. Archer, D.L. The evolution of FDA's policy on *Listeria monocytogenes* in ready-to-eat foods in the United States. *Curr. Opin. Food Sci.* **2018**, *20*, 64–68. [\[CrossRef\]](#)
35. Farber, J.M.; Zwietering, M.; Wiedmann, D.; Schaffner, D.; Hedberg, C.W.; Harrison, M.A.; Hartnett, E.; Chapman, B.; Donnelly, C.W.; Goodburn, K.E.; et al. Alternative approaches to the risk management of *Listeria monocytogenes* in low-risk foods. *Food Control* **2021**, *123*, 107601. [\[CrossRef\]](#)
36. European Commission. Commission Regulation (EC) No 2073/2005 of 15 November 2005 on Microbiological Criteria for Foodstuffs. *Off. J. Eur. Union* **2005**, *338*, 1–26.
37. EFSA Panel on Biological Hazards; Ricci, A.; Allende, A.; Bolton, D.; Chemaly, M.; Davies, R.; Escámez, P.S.F.; Girones, R.; Herman, L.; Koutsoumanis, K.; et al. *Listeria monocytogenes* contamination of ready-to-eat foods and the risk for human health in the EU. *EFSA J.* **2018**, *16*, e05134. [\[CrossRef\]](#) [\[PubMed\]](#)

38. Arvanitoyannis, I.S.; Kotsanopoulos, K.V. Smoking of Fish and Seafood: History, Methods and Effects on Physical, Nutritional and Microbiological Properties. *Food Bioprocess. Technol.* **2012**, *5*, 831–853. [\[CrossRef\]](#)
39. Viktorov, A.G. Invasive Potential and Regulation Experience of Using Transgenic Organisms in Aquaculture by Way of Example of Atlantic Salmon. *Russ. J. Biol. Invasions* **2023**, *14*, 144–150. [\[CrossRef\]](#)
40. Soga, K.; Nakamura, K.; Ishigaki, T.; Kimata, S.; Ohmori, K.; Kishine, M.; Mano, J.; Takabatake, R.; Kitta, K.; Nagoya, H.; et al. Development of a novel method for specific detection of genetically modified Atlantic salmon, AquAdvantage, using real-time polymerase chain reaction. *Food Chem.* **2020**, *305*, 125426. [\[CrossRef\]](#)
41. Lerfall, J.; Hoel, S. Effects of salting technology and smoking protocol on yield and quality of hot-smoked Atlantic salmon (*Salmo salar* L.). *J. Food Process. Preserv.* **2020**, *45*, e15064. [\[CrossRef\]](#)
42. Mantovam, V.B.; dos Santos, D.F.; Giola, L.C., Jr.; Landgraf, M.; Pinto, U.M.; Todorov, S.D. *Listeria monocytogenes*, *Salmonella* spp., and *Staphylococcus aureus*: Threats to the Food Industry and Public Health. *Foodborne Pathog. Dis.* **2025**, *22*, 809–824. [\[CrossRef\]](#)
43. Maughan, L.; Whyte, P.; Bolton, D. The bacterial quality and safety of cold smoked salmon during production and subsequent chilled storage. *J. Appl. Microbiol.* **2025**, *136*, Ixaf035. [\[CrossRef\]](#)
44. Heir, E.; Jacobsen, M.; Gaarder, M.Ø.; Berget, I.; Dalgaard, P.; Jensen, M.R.; Holck, A.L. Microbial Safety and Sensory Analyses of Cold-Smoked Salmon Produced with Sodium-Reduced Mineral Salts and Organic Acid Salts. *Foods* **2022**, *11*, 1483. [\[CrossRef\]](#)
45. Soro, A.B.; Noore, S.; Hannon, S.; Whyte, P.; Bolton, D.J.; O'Donnell, C.; Tiwari, B.K. current sustainable solutions for extending the shelf life of meat and marine products in the packaging process. *Food Pack. Shelf Life* **2021**, *29*, 100722. [\[CrossRef\]](#)
46. Zuckerman, H.; Avraham, R.B. Control of Growth of *L. monocytogenes* in Fresh Salmon using Microgard and Nisin. *Food Sci. Technol.* **2022**, *35*, 543–548. [\[CrossRef\]](#)
47. Chen, R.; Skeens, J.W.; Wiedmann, M.; Guariglia-Oropeza, V. The efficacy of nisin *Listeria monocytogenes* on cold-smoked salmon at natural contamination levels is concentration-dependent and varies by serotype. *Front. Microbiol.* **2022**, *13*, 930400. [\[CrossRef\]](#) [\[PubMed\]](#)
48. Heir, E.; Jensen, M.R.; Aasli, A.W.; Berget, I.; Holck, A.L. Reduction and Growth Inhibition of *Listeria monocytogenes* by Use of Anti-Listerial Nisin, P100 Phages and Buffered Dry Vinegar Fermentates in Standard and Sodium-Reduced Cold-Smoked Salmon. *Foods* **2023**, *12*, 4391. [\[CrossRef\]](#) [\[PubMed\]](#)
49. Duffes, F.; Corre, C.; Leroi, F.; Dousset, X.; Boyaval, P. Inhibition of *Listeria monocytogenes* by in situ produced and semipurified bacteriocins of *Carnobacterium* spp. on vacuum-packed, refrigerated cold-smoked salmon. *J. Food Prot.* **1999**, *62*, 1394–1403. [\[CrossRef\]](#)
50. Nguyen, N.T.X.; Daniel, P.; Pilard, J.F.; Cariou, R.; Frédérique, G.; Leroi, F. Antibacterial activity of plasma-treated polypropylene membrane functionalized with living *Carnobacterium divergens* in cold-smoked salmon. *Food Control* **2022**, *137*, 108903. [\[CrossRef\]](#)
51. Ghalfi, H.; Allaoui, A.; Destain, J.; Benkerroum, N.; Thonart, P. Bacteriocin activity by *Lactobacillus curvatus* CWBI-B28 to inactivate *Listeria monocytogenes* in cold-smoked salmon during 4 degrees C storage. *J. Food Prot.* **2006**, *69*, 1066–1071. [\[CrossRef\]](#)
52. de Vos, P.; Garrity, G.M.; Jones, D.; Kreis, N.R.; Ludwig, W.; Rainey, F.A.; Schleif, K.H.; Whitman, W.B. Bergey's Manual of Systematic Bacteriology. In *The Firmicutes*; Wiley Publishing Group: Hoboken, NJ, USA, 2009; Volume 3.
53. Anacarso, I.; Messi, P.; Condò, C.; Iseppi, R.; Bondi, M.; Sabia, C.; Niederhäusern, S. A bacteriocin-like substance produced from *Lactobacillus Pentosus* 39 is a natural antagonist for the control of *Aeromonas hydrophila* and *Listeria monocytogenes* in fresh salmon fillets. *Food Sci. Technol.* **2014**, *55*, 604–611. [\[CrossRef\]](#)
54. Tomé, E.; Gibbs, P.A.; Teixeira, P.C. Growth control of *Listeria innocua* 2030c on vacuum-packaged cold-smoke salmon by lactic acid bacteria. *Int. J. Food Microbiol.* **2008**, *121*, 285–294. [\[CrossRef\]](#)
55. Katla, T.; Mørset, T.; Aasen, I.M.; Holck, A.; Axelsson, L.; Naterstad, K. Inhibition of *Listeria monocytogenes* in cold smoked salmon by addition of sakacin P and/or live *Lactobacillus sakei* cultures. *Food Microbiol.* **2001**, *18*, 431–439. [\[CrossRef\]](#)
56. Tahiri, I.; Desbiens, M.; Kheadr, E.; Lacroix, C.; Fliss, I. Comparison of different application strategies of divergicin M35 for inactivation of *Listeria monocytogenes* in cold-smoke wild salmon. *Food Microbiol.* **2009**, *26*, 783–793. [\[CrossRef\]](#) [\[PubMed\]](#)
57. Mei, J.; Shen, Y.; Liu, W.; Lan, W.; Li, N.; Xie, J. Effectiveness of Sodium Alginate Active Coatings Bacteriocin EFL4 for the Quality Improvement of Ready-to-Eat Fresh Salmon Fillets during Cold Storage. *Coatings* **2020**, *10*, 506. [\[CrossRef\]](#)
58. Schöbitz, R.P.; Bórquez, P.A.; Costa, M.E.; Ciampi, L.R.; Brito, C.S. Bacteriocin like substance production by *Carnobacterium piscicola* in a continuous system with three culture broths. Study of antagonism against *Listeria monocytogenes* on vacuum packaged salmon. *Braz. J. Microbiol.* **2006**, *37*, 52–57. [\[CrossRef\]](#)
59. Li, Q.; Liang, W.; Lv, L.; Fang, Z.; Defeng, X.; Liao, J.; Liu, Y. Preparation of PCL/lecithin/bacteriocin CAMT6 antimicrobial and antioxidant nanofiber films using emulsion electrospinning: Characteristics an application in chilled salmon preservation. *Food Res. Int.* **2024**, *175*, 113747. [\[CrossRef\]](#)
60. González-Gragera, E.; García-López, J.D.; Boutine, A.; García-Marín, M.L.; Fonollá, J.; Gil-Martínez, L.; Fernández, I.; Martínez-Bueno, M.; Baños, A. Improving the Quality and Safety of Fish Products with Edible Coatings Incorporating Piscicolin CM22 from a Psychrotolerant *Carnobacterium maltaromaticum* Strain. *Foods* **2024**, *13*, 3165. [\[CrossRef\]](#)

61. Todorov, S.D.; Carneiro, K.O.; Lipilkina, T.A.; Do, H.-K.; Miotto, M.; Lindner, J.D.; Chikindas, M.L. Beneficial microorganisms for the health-promoting in oyster aquaculture: Realistic alternatives. *Aquac. Int.* **2024**, *32*, 10085–10107. [[CrossRef](#)]
62. Bastos, M.C.F.; Coelho, M.L.V.; Santos, O.C.S. Resistance to bacteriocins produced by Gram-positive bacteria. *Microbiology* **2015**, *161*, 683–700. [[CrossRef](#)]
63. Chikindas, M.L.; Roopchand, D.E.; Tiwari, S.K.; Sichel, L.S.; Karwe, M.V.; Nitin, N.; Fagundes, V.L.; Popov, I.V.; Tagg, J.R.; Lu, X.; et al. An integrated engineering approach to creating health-modulating postbiotics. *Mol. Nutr. Food Res.* **2026**, *70*, e70326. [[CrossRef](#)]
64. Salminen, S.; Collado, M.C.; Endo, A.; Hill, C.; Lebeer, S.; Quigley, E.M.M.; Sanders, M.E.; Shamir, R.; Swann, J.R.; Szajewska, H.; et al. The International Scientific Association of Probiotics and Prebiotics. *Nat. Rev. Gastroenterol. Hepatol.* **2022**, *19*, 551. [[CrossRef](#)]
65. Chikindas, M.L.; Sichel, L.S.; Popov, I.V.; Tagg, J.R.; Lu, X.; Mitrokhin, O.V.; Todorov, S.D. Postbiotics: What Are They? *Benef. Microbes* **2025**, *ahead of print*.
66. Atanasova, J.; Dalgalarondo, M.; Iliev, I.; Moncheva, P.; Todorov, S.D.; Ivanova, I.V. Formation of Free Amino Acids and Bioactive Peptides During the Ripening of Bulgarian White Brined Cheeses. *Probiot. Antimicrob. Prot.* **2021**, *13*, 261–272. [[CrossRef](#)]
67. Bover-Cid, S.; Holzapfel, W.H. Improved screening procedure for biogenic amine production by lactic acid bacteria. *Int. J. Food Microbiol.* **1999**, *53*, 33–41. [[CrossRef](#)]
68. Todorov, S.D. Diversity of bacteriocinogenic lactic acid bacteria isolated from boza, a cereal-based fermented beverage from Bulgaria. *Food Control* **2010**, *21*, 1011–1021. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.