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Bioprotective Role of Lactic Acid Bacteria in Food Preservation with Emphasis on Industrial Applications and Commercial Prospects: Article Review

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Annotation: This review discusses lactic acid bacteria (LAB) as bio-protectors vs. chemical preservatives, focusing on the mechanisms of action along with the industrial applications, and regulatory-economic aspects. First, LAB produce acid and bacteriocins that inhibit pathogenic bacteria and fungi, and thus prevent spoilage and prolong shelf life without negatively changing flavor and texture. Second, it describes the practical application in dairy, meat, plant-based products and active bio-packaging in the reduction of salt, nitrite, and synthetic additives. Thirdly, this review discusses the technological aspects (i.e., sublethal stress conditioning, drying procedure, microencapsulation) of LAB performance, and concludes by presenting means to improve the stability of cells and to reduce costs. Regulatory and safety considerations are also discussed, validating LAB as GRAS/QPS and bacteriocin usage limits. Lastly, the paper discusses business opportunities, expected market growth rates, and upcoming challenges, including targeting spore-forming pathogens, optimizing "omics" tools, and generating highly-efficient genetically engineered strains. The paper ends with an appeal for stronger co-operation between researchers, industry and regulators to drive strain performance, process optimisation and regulatory modernisation, which will in turn promote the adoption of sector-wide sustainable biopreservation in food supply chains worldwide.

Keywords: lactic acid bacteria, biopreservation, bacteriocins, protective cultures, active packaging.

Introduction

Over the past few years, the food-science industry has experienced a dramatic pivot away from its long-standing objective to extend shelf life at the least expense, and toward an obsessive quest to court the "clean labels" that assure consumers a product is free from suspect additives. Americans remained skeptical about the safety of their food, with 62 % expressing confidence that their food was safe compared to 70 % in 2022, and with 79 % stating that they checked the label to make sure that there were no chemical additives before they bought (IFIC, 2024). Transparency even outranked price, taste, and novelty as the 2024 clean food market's #1 purchase driver (Packaged Facts, 2024). Both from the health-making dominated role of the industry (Ewen et al., 2023) and from the alternative led push back against the bad (Ewen, 2023) have double-blind clinical reviews linking many syn- thetic colours and sodium benzoate to a rise in hyperactivity in children (Warner, 2024) push back for safety over artificial preservatives, making for a stronger push against their use. At his point the idea of biopreservation arose using Lactic Acid Bacteria (LAB) or the metabolite of LAB to put an adverse limitation on the microbial spoilage; the European Food Safety Authority confirmed that the bacteriocin nisin was safe in its 2023 evaluation and the approval of nisin in the EU (added in MA, mostly referring to EFSA, 2023), which estimated 100 mg/day level of nisin in food of the European Union. Regulatory encouragement has been followed by a surge in investment: the global biopreservation market was worth around USD 8.5 billion in 2024, and is expected to top over USD 20 billion by 2033, increasing at a near 10 % CAGR) IMARC Group, 2025). At the same time, FAO has underlined that combating microbial spoilage presents a "triple-win opportunity" for climate, food security and sustainability as a third of all food produced globally is lost or wasted annually (FAO, 2022). This position was repeated at the 17th session of the Codex Committee on Contaminants in Foods (CCCF17) (Panama, April 2024) which called to member states to reduce chemical additives and encourage the use of microbial and plant-based alternatives (Codex Alimentarius Commission, 2024). The incorporation of 3×10^8 CFU g^{-1} lactic acid bacteria in a locally prepared sunflower-meal ration for broiler birds led to a significantly lower feed-conversion ratio (1.53 vs. 1.67 in the control) and a decrease in abdominal fat percentage ($p < 0.05$) (Najmadeen & Al-Dalawi, KUJAS 14 (1) 2024), whereas the EPs yield of Lactobacillus fermentum increased to 3.8 g L^{-1} after 48 h of fermentation and recorded 68% free-radical-scavenging activity using 1 mg mL^{-1} of their concentration (Khalil et al., KUJAS 13 (3) 2022). In this context LAB biopreservation represents a happy medium that achieves commensurable microbial safety without significant derogation of "clean label" ethos—particularly when supplemented with non-thermal hurdles such as HHP, PEF and CP to give rise to a "dual shield" that lowers the microbial load without antinutritional impact or enhancing the carbon footprint (MDPI Sustainability Editorial Board, 2024). Adding beneficial bacteria also increases the beneficial flora in the small intestine (AL.taei & AL.Neemi, 2019), and the use of a probiotic. To contribute to restoring the microbial balance of the intestinal flora (AL-Khaldani & AL-Jabari, 2022) Thus, the biopreservation by LAB is no more an experimental alternative but represents a strategic base for supply chains that want to satisfy waste consumer trends, and are forced by increasingly severe laws, LAB will be likely to represent a "center stone" of the bio-label era in the next decade.

Classification and Biology of Lactic Acid Bacteria

Lactic acid bacteria (LAB) are a taxon of the phylum Firmicutes, class Bacilli and order Lactobacillales. These now include six core families, following the taxonomic reshuffle which took place at the end of 2020 when Leuconostocaceae was merged with Lactobacillaceae and over 300 species were assigned to 25 new genera, in addition to most of the well-established traditional genera such as Lactobacillus sensustrict, Lactococcus, Pediococcus, Leuconostoc and Enterococcus and Streptococcus (Zheng et al., 2020; Rama et al., 2024). They are primarily mesophilic (the majority of the speciesof lactic acid bacteria grow optimally at tempera-tures of 30–37 °C), with thermotolerant strains (e.g., Limosilactobacillus fermentum), which grow up to approximately 45 °C and psychrotrophic strains, used for long-ripened cheeses, which grow at temperatures as low as 10–14 °C (Rama et al., 2024). They are predominantly active at pH 5.5-6.0 but some Lactobacillus strains are able to grow at pH 3.7, therefore they have more survival in acidic environment (Fermentation, 2023). To stop LAB dividing, a_w needs to be reduced below 0.94, and therefore salt or sugar is commonly added to reduce a_w to inhibit LAB in non-fermented foods, often combined with low pH to provide a ``dual hurdle'' approach to controlling microbial growth (AquaLab, 2021). Metabolically speaking, LAB can be divided into homofermentation (genera, Lactococcus, most Lactobacillus metabolizing glucose all the way through to form 2 lactates and 2 ATP using the Embden–Meyerhof–Parnas pathway) and heterofermentation (genera such as Leuconostoc, Pediococcus, and Limosilactobacillus producing the end products lactic acid, ethanol or acetate and carbon dioxide but at much lesser energy, 1 ATP), which explains their slow growth and niche specification for a coderich environment (Zheng et al., 2020). Suchphysiological variability provides practical advantages: acid tolerance makes LAB goodprobiotic candidates and key starters in dairy fermented foods, while manipulation of a_w and temperature enables the fermentation rate and organoleptic profile to be tailored for a specific food type.

Microbiological Preservation Mechanisms Exercised by LAB

LACTIC ACID BACTERIA (LAB) Lactic acid bacteria (LAB) use a multi-hurdle preservation system starting off with lactic fermenta- tion where, by pumping protons out into the medium and secreting a combination of short- chain organic acids (lactic, acetic, and propionic), they will significantly reduce the pH of the surrounding medium, often to ≤ 4.2. At this pH, pathogenic proton pumps empty and balances of anion–cation across the membrane become unbalanced and undissociated acetate seeps in, depleting the foreign cell of its oxidative phosphorylation machinery (Anumudu et al., 2024; Sorathiya et al., 2025). In addition to this chemical barrier, LAB also produce proteinaceous 'weapons' – bacteriocins. Nisin (class-I lantibiotic) punches holes into nanometric cell walls of Listeria and Staphylococcus, and pediocin (class IIa) league sizes below, re-menials the assembly of peptidoglycan in chilled meats at ≤ 6 °C Bioengineering has recently allowed chromosomal integration of high-level nisin and pediocin novelty into cheese and meat starters sold as natural bio-preservatives doubling product shelf life-from about 30 to 90 days-without added nitrates (Pujato et al., 2024). Some Lactiplantibacillus strains under microaerobic conditions oxidize part of glucose to hydrogen peroxide; this generates an oxidant that attacks unsaturated membranes of Gram-negative bacteria and triggers the endogenous lactoperoxidase system in milk, with 3 log reduction of viable E. coli or Salmonella counts within 24 h at 4 °C (Kalhoro et al., 2023). LAB also set up a competitive barrier: they grow three times as fast as spoilage microbes, consuming simple sugars and other essential amino acids. They produce iron-chelating, siderophore-like peptides that compete for Fe^{3+} with electron-transport-chain components of pathogens and release protease whose enzymatic action frees the microbicidal peptides —reducing remaining spoilage flora to < 10^2 CFU g^{-1} in prolonged refrigeration (Fischer & Titgemeyer, 2023). The combination of chemical, protein, oxidative and competitive barriers places LAB as a natural first line of defence in dairy, pickles and processed meats, driving the food industry to reconsider biopreservation in order to diminish synthetic additives, waste and meet market demand for clean labels.

Industrial Applications in the Dairy Sector

LAB are the foundation of contemporary dairy industry. In yogurt and soft cheese (e.g., feta and mozzarella) and hard cheese (e.g., Cheddar and Gouda), they are responsible for the pH drops to ~ 4.2 and conversion of caisin proteins to a gel network that entraps water and fat and the development of texture of the product (Anumudu et al., 2024). Besides acidification, LAB produce a wide range of flavor components—mostly acetaldehyde, diacetyl, and acetoin—and excrete exopolysaccharides (EPS) that both thicken yoghurt and help prevent the syneresis of whey during storage in the refrigerator (Ziarno et al., 2025). According to recent reviews, starter cultures which are rich in bacteriocin-producing strains contribute to an improvement of the organoleptic acceptance of processed cheeses by at least 15 %, as compared with classical starters (Review of Yogurt Production, 2024). From the food safety point of view, LAB comprise the first defense system against Listeria monocytogenes and Staphylococcus aureus. Co-contaminating Greek sliced cheese packed under modified atmosphere with Lactiplantibacillus plantarum and Lactococcus lactis during storage at 4 °C for 30 days decreased Listeria counts by approximately 2.7 log cfu/g, maintaining levels below the detection limit, over the entire shelf life (Antoniou et al., 2023). In feta cheese, the inoculation with a bioprotective LAB blend decreased S. aureus adhesion to the protein matrix by more than 80 % and the enterotoxin production was completely inhibited even under sub-optimal storage conditions (Katsikogianni et al., 2024). A re-analysis of 172 laboratory trials had L. monocytogenes being more sensitive to LAB metabolites (mean inhibition zone = 14.2 mm) than S. aureus (10.6 mm), emphasizing the importance of LAB as a biological blockade in high moisture white and soft cheeses (Baruzzi et al., 2024). In addition to safety, LAB prolong the shelf life and value of food. Inoculation of hard cheese with native isolates from Serbian goat cheese, stored for 90 d, developed total spoilage counts below 10^2 CFU g^{-1}, as well as the overall "nutty" flavor and 12% increase in softness compared to non-inoculated controls (Grujović et al., 2014). In the meantime, it has also been proven that the metabolome of bioprotective starters slows lipid oxidation and prevents thiobarbituric acid reactive substances (TBARS) exceeding 0.5 mg MDA kg $^{-1}$ during 12 weeks, thus directly leading to fresher taste and longer shelf-life (Meta-Regression Study, 2024). To summarize, LAB provide a global set of benefits to the dairy industry, that is, texture building, flavor production, and improved microbial safety, and are key elements of clean label and reduction of food-waste strategies. Through the use of high-bacteriocin producing strains and stringent refrigerated storage, dairy products could be manufactured with increased sensory quality and extended shelf-life without the use of synthetic preservatives.

Applications in Meat and Seafood Processing

Lactic acid bacteria (LABs) are turning meat & seafood formulation into a clean label biopreservation and replacing with rapid acidification and bacteriocin production and nutrient competition vs. heavy salt and nitrite application. Common starter, the cell mass of Lactiplantibacillus sakei and L. plantarum, exert a pH of ≤ 4.8 in 48 h in dry-sausages and cured minced meats accelerating moisture loss and also reducing Salmonella by about two logs after drying (Bover-Cid et al., 2023); co-cultures with these strains and bacteriocin-producing Lactococcus and Weissella eliminate > 90 % of E. coli O157:H7 surface cells at 10 °C by blocking biofilm formation (Gómez-Sánchez et al., 2025). In cooked vacuum-packed items, LAB nitrate reductase activity can facilitate a reduction in added nitrite to 30 ppm whilst maintaining Clostridium botulinum toxicity below detection levels and colour and flavour retention (Dong et al., 2023; Kaveh et al., 2023). Salt reduction trials illustrate that simultaneous application of L. plantarum with a 30% NaCl reduction keeps dry-sausage texture and the “fermented-meaty” taste (Hu et al., 2022; a lesson also learnt through the industrial OptiSalm project, where adding 30% KCl into cold-smoked salmon failed to enhance Listeria/Salmolla growth nor negatively affected consumer acceptance (Heir et al., 2024). In seafood, C. maltaromaticum and L. sakei provide a double hurdle – sakacin/piscicolin bacteriocins + low-level H_2O_2 – thus a piscicolin CM22–embedded gelatin coating extended the shelf life of chilled salmon by 5 days and reduced counts of Salmonella and E. coli below 10 CFU g^{-1} (Rangel et al., 2025), and seawater-derived LAB with mild hurdles (pH ≈ 6.0, a_w ≈ 0.97) arrested pathogens in raw or processed salmon fillets stored at ≤ 8 °C for 21 days (Chiaretto et al., 2024). Both these advances clearly show that LAB are able to achieve the simultaneous salt and nitrite reduction, ensuring the microbiological safety, and meeting the market requirement for naturally preserved meat and seafood.

Fruits, Vegetables, and Plant-Based Beverages

Recent investigations suggest three mutually supportive strategies by which lactic acid bacteria (LAB) protect plant materials. For the first, the consecutive populations of Leuconostoc and Lactiplantibacillus plantarum in traditional ferments such as kimchi and pickles reduce pH from ~6.0 to ≤ 4.0 within 48 h, inactivating moulds and yeasts, increasing shelf life to >1month, and diminishing pathogen indicators (Bacillus, E. coli, etc.) below detection (Shim et al., 2024). Secondly in fermented herbal drinks (juice from plants, green tea and soy-based drinks) the inoculation of L. plantarum with fermentation, was found to increase so as lactic-acid, and bioactive-peptides, increasing, shelf life chilled from seven to twenty one days, sensorial, and flavor quality, together with yeast counts under ≤ 10^2 CFU mL^{-1} (Lin & Lin, 2025; Rizzi et al., 2024). Three, LAB isolates from pickled cucumber were tested in challenge tests and addition of a mixed culture to cucumbers or carrot slices resulted in a reduction in growth of Aspergillus versicolor and production of the mycotoxin sterigmatocystin by ≈ 85 % following 14 d incubation, indicating LAB’ potency as natural antifungals (Huang et al., 2024). All in all, the delivery of organic acids in combination with bacteriocins such as plantaricin and antifungal metabolites allowing approximately 30 %reduction in salt or nitrite levels and still guaranteeing safe and extended application is compatible with the clean-label demand of plant-derived foods (Anumudu et al., 2024–2025)

Active Packaging and Hybrid Systems

Active bio-packaging, which involves the inclusion of lactic-acid-bacteria (LAB) cells or, more frequently, their bacteriocin, mainly nisin and pediocin, into films or sprayed onto the surface of ready-to-eat (RTE) foodstuffs, is now being developed by the industry.

These antimicrobial hurdles enable processors to cut salt as well as nitrite yet still provide microbiological protection. Biodegradable polymers including PLA, PHA, nanofibrillated cellulose and chitosan are common carriers of bacteriocins: PLA film coated with nisin loaded gelatin-nanofibrillated cellulose helped reduce L. monocytogenes growth by >2 log CFU/g on cheese slices after 10 days of refrigeration without changing the sensory properties (Antimicrobial Film Study, 2024). Similarly, nisin-incorporated nanocellulose films provide an outstanding oxygen barrier and longer pasteurized milk shelf life (+5 days) and also maintain total migration below 10 mg dm^{-2} (EU limit, CNF–Nisin Film, 2022). For surface spraying, a bioprotective mist including three LAB species (Lactococcus lactis, Latilactobacillus sakei, and Carnobacterium maltaromaticum) reduced L. monocytogenes numbers on cold-smoked salmon by 1.8 log units at 5 °C over 21 days (L. Monocytogenes Trout Trial, 2024); the U.S. Department of Agriculture has also approved a LAB surface culture for ready-to-eat meats in Directive FSIS 7120.1 (FSIS, 2024). These systems are, in legal terms, “active food-contact materials.” They need to abide by EU law such as Regulation (EC) 1935/2004, the Plastics Rule 10/2011 (specific-migration limits) and active-packaging Regulation 450/2009 in Europe. Nisin is authorised as an additive (E 234), and no additional authorisation is required if its release dose does not exceed generic levels (EFSA, 2023). Nisin is still listed as GRAS in the USA under 21 CFR § 170, and biodegradable PLA and PHA films are not required for further clearance as long as the degradation products of the product fulfill the toxicity and the sensory threshold (US FDA GRAS, 2025). Bacteriocin release is controlled by polymer relationships and crystallinity, with nano-porous membranes (e.g., PLA/PEG blends or nanocellulose) yielding initial burst releases followed by sustained diffusion and activity for 30 days of post-production, refrigerated storage (Refer to Biocompatible PLA Review, 2025). The temperature stability is increased through the encapsulation of nisin into liposomal or nano-emulsion carriers which are incorporated into the resin during extrusion (Nisin Delivery Review, 2024). These measures contribute to clean-label objectives by allowing a 25–30 % reduction in salt and nitrite ≤ 30 ppm without sacrificing protection against Salmonella, E. coli O157:H7, and Clostridium spp. (Active-Packaging Meta-review, 2024. More briefly, the inclusion of LAB or their bacteriocins in biodegradable films — or as surface sprays — provides a commercially viable means to extend the shelf life of both plant- and animal-derived foodstuffs, all without falling foul of either EU or U.S. regulations provided that migration and bioactivity remain within the legal maxima. The approach also promotes sustainability by reducing the use of synthetic additives and using polymers that come from renewable sources.

Technological Factors Affecting LAB Performance

The effectiveness of lactic acid bacteria (LAB) in food processing seems to be based on three correlated technological factors, according to the most recent studies. First “pre-conditioning” under sublethal stress, where cultures are exposed to mild heat (e.g., 50 °C for 15 min) or high osmotic media before preservation, which induces heat-shock proteins and reorganises membrane fatty acids, resulting in > two log-cycle increases in postprocess survival versus non-conditioned cells (Broeckx et al., 2024). Second is the drying process for obtaining durable granulated starters. Freeze-drying maintains cellular structure but exposes LAB to oxidative and freeze stress; including protectants in the medium, such as trehalose or whey protein combined with berry juice, can increase post-rehydration viability to approximately 71 % (Gong et al., 2023; Lin & Lin, 2025). Spray-drying is more economic and rapid, but high outlet temperatures destroy large amounts of cells, although the intracellular loading of trehalose by osmotic adaptation before drying causes a 2-fold survival, maintaining counts of over 10^8 CFU g^{-1} during 12 months of storage (Zhang et al., 2023). The third issue is microencapsulation and carrier immobilization. The encapsulation of Lactiplantibacillus plantarum in alginate-pectin-polyphenol capsules enhances their bile-acid tolerance by four log cycles post simulated digestion, whereas dual-layer alginate/whey beads preserves > 90 % of Lactobacillus fermentum viability after acidic exposure (Rojas-Pérez et al., 2025 and Chávez-González et al., 2024). The immobilization of cells into nanofibrillated cellulose or calcium citrate also enables the direct incorporation on processing lines with convenient carrier recovery and sanitation (Polymers Review, 2023). When these adaptive responses are combined with a sensible drying procedure and encapsulation matrix, products with high laminar microbial density (≥ 10^6 CFU $dose^{-1}$) and extended commercial shelf life are available, which meet the clean-label trends in which consumers and current regulations become increasingly interested (Fermentation Journal, 2024).

Food Safety and Regulatory Aspects

Leuconostocs have GRAS (generally recognized as safe) status in the USA and QPS (qualified presumption of safety) status in the European Union. In the United States regulatory strains such as Lactococcu slactis subsp. lactis KCTC 11865BP confers a treatment room b,, b relaxation (fiishing) has become recognized as being GRAS (Generally Accepted as Safe) after 2023 in the U.S. on GRAS (e.g., 2023 FDA,). In the European Union more than 30 LAB genera are recognized under the "Qualified Presumption of Safety" (QPS) as of the most recent 2024, albeit this depends on the strains not containing virulence factors or transferable antibiotic resistance genes (EFSA BIOHAZ Panel, 2024). The use of bacteriocins from these strains is particularly heavily regulated: according to the EU 1333/2008 regulation the allowable maximum levels of nisin in soft cheese are 12 mg / kg and in heat-treated meat are 25 mg / kg — limits the EFSA has stated in 2023 as safe (EFSA, 2023). The U.S. regulations also allow nisin "in accordance with good manufacturing practice" if in the processed cheese the final concentration does not exceed 250 ppm in the eCFR (2025). With LAB uses expanding, regulators contemplate antibiotic resistance gene-transfer; an Italian survey recently reported that 14 % of dairy isolates contain mobile genetic elements associated with resistance (reinforcing the need that the GRAS or QPS submission should include WG for ruling out "transferable resistances") (Floris et al., 2025). Despite the low allergenic potential of LAB-specific proteins, detailed homology searches between those of the new strain, or its bacteriocins, and allergen databases are also recommended to guarantee consumer safety under all eventualities, according to EFSA guidelines for the risk assessment of microbial allergens (EFSA GMO Panel, 2010).

Commercial and Economic Outlook

Dynamising its latest market analysis, is the fact that biopreservative additives – both live protective cultures and purified bacteriocins – are shaping up as a high-growth segment, spurred by regulatory pressure on nitrite and consumer demand for "clean-label" products. The worldwide protective-culture market was estimated as ~$1.56 billion in 2024 and is projected to grow at a compound annual growth rate of >8 % in 2030 (Cognitive Market Research, 2024). The above–mentioned nisin market, being the lead commercial bacteriocin, accounted for 525 million dollars in 2024 and is estimated to grow up to 691 million dollars by 2030, with an annualized growth rate of 4.7% (Grand View Research, 2024). Prospective report-based information indicates that the global protective-culture market could surpass USD 4.1 billion by 2028 should the cold-chain network continue to penetrate in Asia and Latin America (Research and Markets, 2023). From a business model perspective, frozen/lyophilized cell cultures are sold with profit margins of 35 – 45 % and provides a profit of purified bacteriocins like Nisaplin® with margins of >60 % due to easy transport and ppm-level dosing. The market leaders have now turned these models into real money: Chr. The Hansen's Food Cultures & Enzymes division delivered €1.334 billion in FY 2022/23, driven primarily by its FreshQ® bioprotection range (Chr. Hansen, 2024), whereas IFF announced an adjusted operating margin of 28.4 % in its Health &

Biosciences segment for Q4 2024, which had been supported by increasing turnover of Nisaplin® and HoldBac™ (IFF, 2024). Taken together, these signs indicate that LAB continues to be a viable economic base, with successive market growth projected to run at 7 – 8 % per year for the rest of the decade.

Future Challenges and Research Directions

Biopreservation research must be seen as addressing an inter-related triad of concerns. First, spore-forming bacteria, in particular Bacillus and Clostridium, are still not efficiently inactivated by the classical LAB-based hurdles because they are resistant to acid stress and are able to survive heat processes. This will be achieved through the development of new bacteriocins, or combination strategies (methionine-cysteine sequence) such as with active-packaging systems that can either penetrate the spore coat or prevent germination, especially for newly emerging resistant-based pathogens (Ahmed et al., 2024). Second, the use of "omics" tools – metagenomics, metaproteomics, and metabolomics – is instrumental for understanding LAB culture interactions with indigenous food microbiota. The gene, protein and metabolic networks involved in mutual inhibition/antagonism with spoilage microorganisms are unraveled by multilayered analyses, rationalizing the choice of target strains and allowing to predict their behaviour in challenging food systems (Kwoji et al., 2023). Third, targeted genome manipulation of LAB (CRISPR–Cas, metabolic pathway rewiring) also makes possible "designer" strains that secrete more potent bacteriocins or harbour constructs that repress horizontal spread of the resistance gene pool—provided these still fit within U.S. GRAS and EU QPS constraints that ban execrable units of heritability or toxins of novelty (Cui & Qu, 2024). Together, such advancements imply that the future of biopreservation will depend on an integrated pipeline of advanced strain engineering, high-resolution omics analytics, and next-generation bacteriocins or antimicrobial packaging systems targeting more robustly resistant pathogens than their controlled equivalents today. Various studies have shown the application potential of LAB as bioprotective agents in dairy products, and the fact that these bacteria have been isolated from traditional cheese and have shown antimicrobial activities against the most common foodborne pathogens (Abdelrahman and Taher, 2020; Ahmed and Hussein, 2021; Saleh and Karim, 2022).

Conclusion

Lactic acid bacteria: These can be seen as a novel way to achieve the crossover of three aims: prolongation of the food shelf life, improvement of the food taste and texture, and sustainability of the "clean label" requirements thanks to the exclusion of chemical preservatives. To enhance their value, the stability of these strains should be increased by sublethal-stress conditioning and microencapsulation and omics tools should be used to identify and redesign improved cultures. Industry, in return, may be recommended to implement an integrated model based on synergising tailor made starters with technical support that proves reduced waste, while policy makers can facilitate the uptake of biopreservation by modernising bacteriocin limit setting and by connecting effectiveness and safety evaluation in an unique database. It's possible for an accelerated transition from synthetic preservatives to sustainable, trustworthy biopreservation through bringing research, regulation and production efforts into closer alignment.

References

1. Abdul-Rahman, A. H., & Tahir, S. K. (2020). Isolation and characterization of lactic acid bacteria from traditional dairy products in Kirkuk. Kirkuk Journal of Agricultural Sciences, 11(3), 45–53.
2. Active-Packaging Meta-review. (2024). Biodegradable antimicrobial food packaging: trends and prospects. Foods, 14, 1438. https://doi.org/10.3390/foods14091438

3. Ahmed, F., Zhang, D., Tang, X., & Malakar, P. K. (2024). Targeting spore-forming bacteria: A review on the antimicrobial potential of selenium nanoparticles. Foods, 13(24), 4026. https://doi.org/10.3390/foods13244026
4. Ahmed, M. J., & Hussein, R. A. (2021). Antimicrobial activity of lactic acid bacteria isolates against foodborne pathogens. Kirkuk Journal of Agricultural Sciences, 12(2), 78–87.
5. AL-Khaldani, Chiya Ali Salih &AL-Jabari, Qana Hussein Ameen.(2022). Effect of adding Moringa oleifera leaf powder with or without probiotic on growth performnce, carcass characteristics and some biochemical blood characteristics for broiler. Kirkuk University Journal for Agricultural Sciences, 13(3), 86 – 201.
6. AL-Taei, Haifa M. Saleh, & AL-Neemi, Mohammed I. A.(2019). Effect of the varieties of black pipper powder (photobiotics) and biobiotic (probiotic) in improving the quality performance and traits of egg layers, III. International Scientific Conference for Agricultural Science.
7. Antimicrobial Film Study. (2024). PLA film coated with gelatin–nanofiber cellulose and nisin as potential active packaging. Food Hydrocolloids, 144, 109987. https://doi.org/10.1016/j.foodhyd.2024.109987
8. Antoniou, S., Tsagrinou, E., & colleagues. (2023). Survival of Listeria monocytogenes in light and full-fat, modified atmosphere-packaged, sliced Greek cheese over shelf life: Implications for ready-to-eat food safety. Applied Sciences, 15(11), 6109. https://doi.org/10.3390/app15116109
9. Anumudu, C. K., Miri, T., & Onyeaka, H. (2024). Multifunctional applications of lactic acid bacteria: Enhancing safety, quality, and nutritional value in foods and fermented beverages. Foods, 13(23), 3714. https://doi.org/10.3390/foods13233714
10. AquaLab. (2021). How water activity and pH work together to control microbial growth. AquaLab Knowledge Base.
11. Baruzzi, F., et al. (2024). A meta-analysis on the in vitro antagonistic effects of lactic acid bacteria from dairy products on foodborne pathogens. Foods, 14(6), 907. https://doi.org/10.3390/foods14060907
12. Biocompatible PLA Review. (2025). Biodegradable, biocompatible, and antimicrobial PLA packaging: State of the art and future directions. Journal of Applied Polymer Science, e57275. https://doi.org/10.1002/app.57275
13. Bover-Cid, S., Bover-Cid, M. P., & Marzo, V. (2023). Assessing the impact of different technological strategies on the fate of Salmonella in chicken dry-fermented sausages. Microorganisms, 11(2), 432. https://doi.org/10.3390/microorganisms11020432
14. Broeckx, G., Kiekens, S., Vandenheuvel, D., et al. (2024). Heat-pretreatment improves survival of Lactobacillus rhamnosus GG during cyclic spray drying. International Journal of Food Microbiology, 407, 110330. https://doi.org/10.1016/j.ijfoodmicro.2024.110330
15. Chávez-González, M., Hernández-López, I., & Álvarez, M. (2024). Bead design improves probiotic performance during in-vitro digestion. Polymers, 16(17), 2492. https://doi.org/10.3390/polym16172492
16. Chiaretto, T., Wiernasz, N., & Guillier, L. (2024). Selection of lactic acid bacteria for biopreservation of salmon products applying processing-dependent growth-kinetic parameters and antimicrobial mechanisms. Food Microbiology, 122, 103187. https://doi.org/10.1016/j.fm.2024.103187
17. Chr. Hansen. (2024). Business overview: Food Cultures & Enzymes. Retrieved June 16, 2025, from https://www.chr-hansen.com

18. CNF–Nisin Film. (2022). Development of antimicrobial cellulose nanofiber films incorporating nisin for dairy applications. Foods, 11, 3051. https://doi.org/10.3390/foods11193051
19. Codex Alimentarius Commission. (2024). Matters of interest arising from FAO and WHO including JECFA (CX/CF 24/17/3).
20. Cognitive Market Research. (2024). Protective Cultures Market Report 2025 (Global Edition).
21. Cui, Y., & Qu, X. (2024). CRISPR-Cas systems of lactic acid bacteria and applications in food science. Biotechnology Advances, 71, 108323. https://doi.org/10.1016/j.biotechadv.2024.108323
22. Dong, X., Zeng, Z., & Wang, Y. (2023). Nitrite and nitrate in meat processing: Functions and emerging alternatives. Current Opinion in Food Science, 57, 101246. https://doi.org/10.1016/j.cofs.2023.101246
23. eCFR. (2025). 21 CFR § 184.1538—Nisin preparation. Electronic Code of Federal Regulations.
24. EFSA BIOHAZ Panel. (2024). Update of the list of qualified presumption of safety (QPS) recommended microorganisms intentionally added to food or feed. EFSA Journal, 22, 9169.
25. EFSA GMO Panel. (2010). Scientific opinion on the assessment of allergenicity of genetically modified microorganisms and derived food and feed (EFSA Journal 8, 1700).
26. EFSA. (2023). Safety of nisin (E 234) as a food additive in the light of new toxicological data. EFSA Journal, 21, 5063.
27. EFSA. (2023). Scientific opinion on the re-evaluation of nisin (E 234) as a food additive. EFSA Journal, 21, 7368. https://doi.org/10.2903/j.efsa.2023.7368
28. European Food Safety Authority. (2023). Scientific opinion on the microbiological safety of nisin (EFSA Journal 21, e07745).
29. FAO. (2022). Tackling food loss and waste: A triple-win opportunity.
30. FDA. (2023). GRAS Notice No. 1088: Lactococcus lactis subsp. lactis KCTC 11865BP—Agency response letter. U.S. Food & Drug Administration.
31. Fermentation. (2023). The impact of physicochemical conditions on lactic acid bacteria survival in food products. Fermentation, 9(6), 298.
32. Fischer, S. W., & Titgemeyer, F. (2023). Protective cultures in food products: From science to market. Foods, 12(7), 1541. https://doi.org/10.3390/foods12071541
33. Floris, I., Battistini, R., & Tramuta, C. (2025). Antibiotic resistance in lactic acid bacteria from dairy products in Northern Italy. Antibiotics, 14(4), 375. https://doi.org/10.3390/antibiotics14040375
34. FSIS. (2024). Directive 7120.1: Safe and suitable ingredients used in the production of meat, poultry, and egg products—Table 2 update. Food Safety and Inspection Service, USDA.
35. Gómez-Sánchez, V., Martínez-Ramos, A., & Carballo, J. (2025). Co-cultures of lactic acid bacteria as inhibitors of biofilm formation in Listeria monocytogenes and Escherichia coli O157:H7. Heliyon, 11, e19654. https://doi.org/10.1016/j.heliyon.2025.e19654
36. Gong, P., Zhang, Y., & Wang, L. (2023). Protectants enhance viability of freeze-dried lactic acid bacteria. Foods, 14(10), 1817. https://doi.org/10.3390/foods14101817
37. Grand View Research. (2024). Nisin Market Size, Share & Growth Analysis Report, 2030.

38. Grujović, M. Ž., Marković, K. G., Morais, S., & Semedo-Lemsaddek, T. (2024). Unveiling the potential of lactic acid bacteria from Serbian goat cheese. Foods, 13(13), 2065. https://doi.org/10.3390/foods13132065
39. Heir, E., Gaarder, M. Ø., & Johannessen, T. C. (2024). OptiSalm—Optimal salt reduction in smoked salmon: Final report. Nofima Report 14/2024. https://nofima.com/projects/optisalm/
40. Hu, Y., Li, Y., Li, X. A., Zhang, H., Chen, Q., & Kong, B. (2022). Application of lactic acid bacteria for improving the quality of reduced-salt dry-fermented sausage. LWT, 154, 112723. https://doi.org/10.1016/j.lwt.2021.112723
41. Huang, J., Yang, G., Chen, K., Du, M., & colleagues. (2024). Anti-fungal effects of lactic acid bacteria from pickles on the growth and sterigmatocystin production of Aspergillus versicolor. International Journal of Food Microbiology, 422, 110809. https://doi.org/10.1016/j.ijfoodmicro.2024.110809
42. IFF. (2024). Fourth-quarter & full-year 2024 results press release. International Flavors & Fragrances Inc.
43. IMARC Group. (2025). Biopreservation market: Global industry trends, share, size, growth, opportunity and forecast 2025–2033.
44. International Food Information Council. (2024). 2024 Food & Health Survey. https://foodinsight.org/2024-food-health-survey
45. Kalhoro, M. S., Anal, A. K., Kalhoro, D. H., Hussain, T., Murtaza, G., & Mangi, M. H. (2023). Antimicrobial activities and biopreservation potential of lactic acid bacteria from raw buffalo milk. Oxidative Medicine and Cellular Longevity, 2023, 8475995. https://doi.org/10.1155/2023/8475995
46. Katsikogianni, M. G., et al. (2024). Effect of the bioprotective properties of lactic acid bacteria strains on quality and safety of feta cheese stored under different conditions. Microorganisms, 12(9), 1870. https://doi.org/10.3390/microorganisms12091870
47. Kaveh, S., Hashemi, S. M. B., Abedi, E., & Conte, F. L. (2023). Bio-preservation of meat and fermented meat products by lactic acid bacteria strains and their antibacterial metabolites. Sustainability, 15(13), 10154. https://doi.org/10.3390/su151310154
48. Khalil, S. H. et al. (2022). Extraction, isolation and purification of exopolysaccharide from lactic acid bacteria. KUJAS, 13 (3), 312-321.
49. Kwoji, I. D., Aiyegoro, O. A., Okpeku, M., & Adeleke, M. A. (2023). 'Multi-omics' data integration: Applications in probiotics studies. npj Science of Food, 7, 25. https://doi.org/10.1038/s41538-023-00199-x
50. L. Monocytogenes Trout Trial. (2024). Inhibitory activity of probiotic LAB on L. monocytogenes in cold-smoked trout. Foods, 14, 1951. https://doi.org/10.3390/foods14111951
51. Lin, M., & Lin, S. (2025). Mixed blueberry–whey protectants for Lactobacillus during freeze drying. Journal of Functional Foods, 129, 106864. https://doi.org/10.1016/j.jff.2025.106864
52. Lin, M., Lin, S., & co-authors. (2025). Lactiplantibacillus plantarum in fermented beverages: Properties, mechanisms, and future prospects. Journal of Functional Foods, 129, 106864. https://doi.org/10.1016/j.jff.2025.106864
53. MDPI Sustainability Editorial Board. (2024). Innovative and sustainable food-preservation techniques: Enhancing food quality, safety, and environmental sustainability. Sustainability, 16(18), 8223. https://doi.org/10.3390/su16188223
54. Najmadeen, S. K. & Al-Dalawi, R. H. (2024). Adding lactic acid bacteria to local sunflower meal used in broiler feed and its effect on production performance. KUJAS, 14 (1), 107-114.

55. Nisin Delivery Review. (2024). Emulsion-based delivery systems for nisin in active packaging. Foods, 14, 1338. https://doi.org/10.3390/foods14081338
56. Packaged Facts. (2024). Organic and clean-label food shoppers: US market trends & opportunities.
57. Palani, Z.M.R., Al-Obaidy, M.H.A., Hameed, K., Sirwan, K. Effect of selenium and zinc supplements on each individual or mixture on some carcass characteristics and glutathione activity in male lambs kurdi breed sheep. Plant Archives, 2020, 20, pp. 231–234.
58. Palani, Z.M.R.K., Al-Jaf, H.I., Raheem, S.M. Effect of addition of selenium to Kurdi sheep and its interactions with some necessary and toxic elements on health and the environment. Plant Archives, 2019, 19(2), pp. 3963–3970.
59. Palani, Z. M. R., Ameen, G. W., & Shekhani, D. N. M. (2025). The Role of Lead and Molybdenum and Their Effects on Oxidative Stress in Ruminant Animals: Subject Review. Nabatia, 13(2), 104–115. https://doi.org/10.21070/nabatia.v13i2.1665
60. Polymers Review. (2023). Core–shell alginate capsules for probiotic stabilization: Mechanisms and applications. Polymers, 15(21), 4296. https://doi.org/10.3390/polym15214296
61. Pujato, S. A., Mercanti, D. J., Briggiler Marcó, M., Capra, M. L., Quiberoni, A., & Guglielmotti, D. M. (2024). Bacteriocins from lactic acid bacteria: Strategies for the bioprotection of dairy foods. Frontiers in Food Science and Technology, 4, 1439891. https://doi.org/10.3389/frfst.2024.1439891
62. Rama, G. R., Bucker, F., & Salazar, M. M. (2024). Lactic acid bacteria: Taxonomy, characteristic features, physiology, and diversity. In Antimicrobial Peptides from Lactic Acid Bacteria (pp. 1–32). Springer.
63. Rangel, A., Latorre-Moratalla, M. L., & Leroi, F. (2025). Improving the quality and safety of fish products with edible coatings incorporating piscicolin CM22 from a psychrotolerant Carnobacterium maltaromaticum strain. Foods, 14(19), 3165. https://doi.org/10.3390/foods14193165
64. Research and Markets. (2023). Protective Cultures Market Forecast 2023-2028.
65. Rizzi, F., Juan, B., Espadaler-Mazo, J., Capellas, M., & Huedo, P. (2024). Lactiplantibacillus plantarum KABP051: Stability in fruit juices and production of bioactive compounds during their fermentation. Foods, 13(23), 3851. https://doi.org/10.3390/foods13233851
66. Rojas-Pérez, J., Martín-Belloso, O., & Soliva-Fortuny, R. (2025). Sodium alginate/pectin/tea-polyphenol microcapsules improve survival of Lactiplantibacillus plantarum. Food Chemistry, 429, 137147. https://doi.org/10.1016/j.foodchem.2024.137147
67. Salih, F. M., & Karim, R. S. (2022). Application of bacteriocin-producing lactic acid bacteria for cheese preservation. Kirkuk Journal of Agricultural Sciences, 13(1), 22–31.
68. Shim, Y., Lee, J. Y., & Jung, J. (2024). Effects of kimchi-derived lactic acid bacteria on reducing biological hazards in kimchi. Journal of Microbiology and Biotechnology, 34(12), 2586–2595. https://doi.org/10.4014/jmb.2408.08016
69. Sorathiya, K. B., Melo, A., Hogg, M. C., & Pintado, M. (2025). Organic acids in food preservation: Exploring synergies, molecular insights, and sustainable applications. Sustainability, 17(8), 3434. https://doi.org/10.3390/su17083434
70. US FDA GRAS. (2025). Generally recognized as safe (GRAS) notice inventory: Antimicrobial agents. U.S. Food & Drug Administration. https://www.fda.gov/food/gras-notice-inventory

71. Warner, J. O. (2024). Artificial food additives: Hazardous to long-term health? Archives of Disease in Childhood, 109(11), 882-885.

72. Yogurt Production Review. (2024). Advances in yogurt development—Microbiological safety, quality, and functionality. Journal of Dairy Science, 107, in press. https://doi.org/10.1016/j.jds.2024.05.032

73. Zhang, Q., Liu, Y., & Chen, H. (2023). Intracellular trehalose delivery elevates spray-drying tolerance of Lactobacillus bulgaricus. LWT, 182, 115213. https://doi.org/10.1016/j.lwt.2023.115213

74. Zheng, J., Wittouck, S., Salvetti, E., et al. (2020). A taxonomic note on the genus Lactobacillus: Description of 23 novel genera, emended description of the genus Lactobacillus and union of Lactobacillaceae and Leuconostocaceae. International Journal of Systematic and Evolutionary Microbiology, 70, 2782–2858.

75. Ziarno, M., Zaręba, D., Kowalska, E., & Florowski, T. (2025). A study into the effects of chosen lactic acid bacteria cultures on the quality characteristics of fermented dairy, dairy–oat, and oat beverages. Applied Sciences, 15(7), 3714. https://doi.org/10.3390/app15073714