Natural Preservatives and Emerging Technologies for Sustainable Fish Preservation: Nutritional, Health, and Consumer Perspectives

Dr.Ch.Lalitha, Lecturer in Microbiology, Government College for Women(A), Srikakulam

Abstract

Fish and seafood provide high-quality proteins, essential amino acids, omega-3 fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), along with key vitamins and minerals that contribute to human health. Despite this nutritional richness, their high water activity, neutral pH, and lipid profile make them highly susceptible to rapid spoilage driven by microbes, enzymes, and oxidative reactions [1,2]. Traditional practices—including chilling, freezing, salting, drying, and smoking—help delay deterioration but frequently compromise sensory and nutritional quality [3]. To address these limitations, recent work has focused on natural preservation agents, such as plant-derived extracts, essential oils, organic acids, chitosan, and peptides obtained from fish processing by-products [4–7]. At the same time, emerging non-thermal technologies—such as high-pressure processing, pulsed electric fields, ultraviolet light, ozone application, and modified atmosphere packaging—have been shown to extend shelf life while maintaining product integrity [8–11]. Growing consumer concerns about synthetic preservatives have accelerated interest in “clean-label” seafood products. Combining natural preservatives with innovative processing techniques, often referred to as multi-hurdle strategies, appears to be one of the most promising directions for sustainable seafood preservation. This review compiles recent advances on the nutritional role of fish, conventional and emerging preservation methods, bioactive compounds, and health implications, with emphasis on environmentally responsible processing approaches.

Keywords: Fish preservation; Seafood processing; Nutritional value; Natural preservatives; Bioactive compounds; Non-thermal technologies; Shelf-life extension; Sustainable food systems

1. Introduction

Fish and aquatic foods make a vital contribution to human diets worldwide, supplying around one-fifth of average per capita animal protein [1]. Beyond their role as a protein source, they are also rich in indispensable amino acids, long-chain omega-3 fatty acids such as EPA and DHA, and important micronutrients including iodine, selenium, and vitamin D [2]. Together, these nutrients support cardiovascular and neurological health, immune function, and overall metabolic balance.

However, fish deteriorate rapidly after harvest because their composition and physiology create favorable conditions for spoilage. High moisture content, near-neutral pH, active enzymes, and a lipid fraction prone to oxidation all accelerate microbial activity and quality loss [3]. The problem is especially acute in warm regions where refrigeration and cold-chain systems are inadequate, resulting in significant nutritional and economic waste [4].

Conventional preservation approaches—such as chilling, freezing, salting, drying, and smoking—are still widely applied but often lead to undesirable changes in texture, flavor, or nutrient profile [5]. With rising interest in minimally processed and "clean-label" foods, there is growing pressure to reduce chemical additives while maintaining safety and quality [6]. This has encouraged the exploration of naturally derived preservatives and modern, non-thermal processing techniques that can extend shelf life without compromising product integrity [7,8].

The purpose of this review is to summarize the nutritional relevance of fish, describe traditional and emerging preservation methods, discuss natural bioactive compounds with preservative potential, and highlight innovative technologies and health perspectives, with particular focus on sustainable strategies for future seafood processing.

2. Nutritional Value of Fish

2.1 Proteins and Bioactive Peptides

Proteins from fish are easily digested and supply all of the essential amino acids required for human health. In addition to their nutritional role, proteins can be hydrolyzed into shorter fragments—bioactive peptides—through enzymatic treatment or by valorizing by-products such as skin, viscera, or bones. These peptides have been reported to exert antioxidant, blood pressure–regulating, antimicrobial, and immune-modulating effects, which makes them promising as functional food ingredients. Using fish by-products in this way not only adds nutritional value but also supports sustainability by reducing waste in seafood processing [9–13].

2.2 Lipids and Omega-3 Fatty Acids

Marine fish are an important dietary source of polyunsaturated fatty acids, particularly the long-chain omega-3 lipids EPA and DHA. These compounds are associated with improved cardiovascular health, anti-inflammatory actions, neurological development, and benefits for pregnancy and early childhood. The fatty acid profile varies among species and habitats, highlighting the need for diverse fish consumption to achieve balanced intake [12,14,15].

2.3 Vitamins

Fish also provides a range of vitamins, including fat-soluble A and D, which are critical for visual health, immune defense, calcium absorption, and skeletal strength. The B-vitamin group is well represented, with vitamin B12 being especially abundant in fish and vital for neurological function and red blood cell production, while vitamin B6 contributes to amino acid metabolism and neurotransmitter synthesis [16,17].

2.4 Minerals

Seafood contributes essential minerals such as selenium, iodine, zinc, calcium, and phosphorus. Selenium helps protect against oxidative stress and supports thyroid function, whereas iodine is indispensable for the synthesis of thyroid hormones. These minerals are generally more bioavailable in fish compared to plant foods, making regular fish consumption important for preventing deficiencies in human populations [18].

3. Traditional Preservation Methods

3.1 Chilling and Refrigeration

Lowering the temperature of fresh fish immediately after harvest is one of the most widely used strategies to slow microbial activity. Storage in ice or refrigerated systems is relatively inexpensive and effective for short-term preservation. However, prolonged chilling often results in quality deterioration due to drip loss, protein unfolding, and oxidative damage to lipids [19].

3.2 Freezing

Maintaining fish at sub-zero temperatures (–18 °C or below) can halt the activity of most spoilage organisms and enzymes, thereby greatly extending shelf life. Nevertheless, repeated cycles of freezing and thawing compromise muscle structure, leading to undesirable textural changes. In addition, long-term frozen storage may still permit gradual oxidative rancidity and protein degradation [20].

3.3 Salting

Reducing the available water in fish muscle through salting creates conditions that are unfavorable for microbial proliferation. Both dry salting and brining remain traditional practices in many regions. Health concerns regarding excessive sodium consumption have prompted research into partial substitution with other salts such as potassium chloride, as well as the use of flavor enhancers to preserve consumer acceptance [21].

3.4 Drying

Dehydration has long been used to extend the shelf life of fish, with methods ranging from sun drying and hot-air ovens to modern freeze-drying. While effective in lowering water activity, drying may also lead to nutrient degradation and lipid oxidation. Recent innovations—including vacuum drying and improved solar dryer designs—offer more efficient processes with better retention of quality [22].

3.5 Smoking

Smoking combines preservation with flavor enhancement by exposing fish to smoke constituents that inhibit microbial activity. However, conventional smoking can generate hazardous polycyclic aromatic hydrocarbons (PAHs). To address this issue, techniques such as liquid smoke application and controlled smoking systems have been developed to reduce PAH levels while maintaining desired sensory properties [23,24].

4. Natural Preservatives and Bioactive Compounds

4.1 Plant Extracts and Essential Oils

Many herbs and spices—including rosemary, thyme, oregano, clove, and cinnamon—are rich in phenolic constituents with both antioxidant and antimicrobial potential. When incorporated into fish products, their essential oils can suppress bacterial growth and slow oxidative changes in lipids. A challenge, however, is that these oils often impart intense aromas or flavors, which has led to the adoption of strategies such as controlled dosing, encapsulation, or incorporation into edible films to balance efficacy with consumer acceptability [25–27].

4.2 Chitosan and Edible Coatings

Chitosan, obtained by deacetylation of chitin from crustacean shells, is one of the most widely studied natural polymers in seafood preservation. It not only forms protective films around fish muscle but also possesses inherent antimicrobial activity. Application as coatings has been shown to delay microbial proliferation and reduce oxidative rancidity. When combined with other natural preservatives such as essential oils or plant extracts, its protective effect is enhanced. Advances in nanotechnology have also enabled the development of nano-chitosan and composite films that improve stability and functional performance [28,29].

4.3 Organic Acids and Bacteriocins
Organic acids—including acetic, lactic, and citric acid—exert preservative effects by lowering pH and disrupting microbial metabolism. They are often applied as dips or incorporated into packaging to suppress spoilage organisms. In parallel, bacteriocins such as nisin are naturally occurring antimicrobial peptides produced by lactic acid bacteria that can selectively target foodborne pathogens in seafood. Combining acids and bacteriocins with other natural preservatives has been found to create synergistic effects and prolong shelf life [30,31].

4.4 Bioactive Peptides from Fish By-products
Fish processing by-products such as skin, bones, and viscera can be enzymatically hydrolyzed to release bioactive peptides. These compounds have demonstrated antioxidant and antimicrobial properties, making them candidates for natural preservation. Their utilization also aligns with circular economy principles, as they transform what would otherwise be waste into value-added functional ingredients [32,33].

5. Innovative Non-Thermal Technologies

5.1 High-Pressure Processing (HPP)
High-pressure processing is a non-thermal technique that subjects foods to pressures in the range of 200–600 MPa. This disrupts microbial membranes and inactivates enzymes without applying high temperatures, thereby extending shelf life while retaining nutritional and sensory characteristics. In seafood, HPP has been successfully tested on species such as salmon, cod, and hake, where it improves safety and slows spoilage [34–36].

5.2 Pulsed Electric Fields (PEF)
Pulsed electric field treatment involves exposing food to very short, high-voltage pulses that create pores in microbial membranes and reduce enzymatic activity. While the method is most advanced for liquid foods, recent research has explored its use in seafood marinades and brines. In such applications, PEF not only reduces microbial load but also enhances mass transfer, which can be used to control salt uptake in processed fish [37].

5.3 Ultraviolet (UV) Irradiation
Ultraviolet-C light, typically in the 200–280 nm range, causes structural damage to microbial DNA, leading to reduced contamination on fish surfaces. Its effectiveness is limited by poor penetration, and excessive exposure may accelerate lipid oxidation. For these reasons, UV treatment is often paired with protective packaging or antioxidant agents to improve efficacy [38].

5.4 Ozone Treatment
Ozone, delivered either as a gas or dissolved in chilled water, is a powerful antimicrobial that can reduce bacterial, viral, and fungal contamination on seafood. It is commonly applied for

washing fish or sanitizing storage environments. However, careful control of concentration is essential, since high levels may trigger oxidative damage to fish lipids and proteins [39].

5.5 Modified Atmosphere Packaging (MAP)
Modified atmosphere packaging preserves seafood by adjusting the ratio of gases inside the package—most often by increasing carbon dioxide and lowering oxygen. This slows microbial metabolism and oxidative spoilage, while also helping retain texture and sensory quality. MAP is generally used in combination with refrigeration and requires packaging materials that can maintain the selected gas balance throughout storage [40].

6. Health Perspectives and Consumer Trends

Growing concerns regarding the safety of synthetic preservatives—linked in some studies to adverse health effects such as carcinogenicity or allergic reactions—have shifted consumer preferences toward natural alternatives. In today's markets, shoppers show strong interest in products that carry "clean-label," "organic," or "free from additives" claims. Natural antimicrobials, edible coatings, and emerging non-thermal preservation methods correspond well with these expectations, as they aim to extend shelf life without compromising safety or quality [41,42].

From a policy standpoint, regulatory agencies are increasingly supportive of sustainable and environmentally responsible preservation strategies. Approaches that minimize synthetic additives, reduce energy consumption, and valorize seafood by-products not only enhance food safety but also contribute to circular economy initiatives and resource efficiency [43].

7. Future Directions and Conclusion

Looking ahead, sustainable seafood preservation will depend on combining naturally derived preservatives with innovative non-thermal technologies in ways that maintain safety, nutrition, and consumer trust. Applying a multi-hurdle strategy—where different preservation methods are used in synergy—offers a pathway to reduce dependence on synthetic additives while improving overall efficacy.

Equally important is the movement toward a circular bioeconomy, where fish processing by-products are transformed into bioactive peptides, coatings, or other functional ingredients rather than wasted. This not only supports environmental sustainability but also creates added economic value for the seafood sector.

Future studies should prioritize consumer perception, cost-effectiveness, and regulatory approval of these emerging technologies. Demonstrating scalability from laboratory research to industrial applications will be key to ensuring that innovative preservation approaches can be widely adopted across global seafood supply chains.

References:

1. FAO. The State of World Fisheries and Aquaculture 2022. Sustainability in action. Rome: Food and Agriculture Organization of the United Nations; 2022.

2. Tacon AGJ, Metian M. Fish matters: importance of aquatic foods in human nutrition and global food supply. Rev Fish Sci Aquac. 2013;21(1):22–38.
3. Gram L, Huss HH. Microbiological spoilage of fish and fish products. Int J Food Microbiol. 2009;33(1):121–137.
4. Shahidi F, Ambigaipalan P. Phenolics and polyphenolics in foods, beverages and spices: antioxidant activity and health effects – a review. J Funct Foods. 2015;18:820–897.
5. Ghaly AE, Dave D, Budge S, Brooks MS. Fish spoilage mechanisms and preservation techniques: review. Am J Appl Sci. 2010;7(7):859–877.
6. Olatunde OO, Benjakul S. Natural preservatives for extending the shelf life of seafood: a revisit. Compr Rev Food Sci Food Saf. 2018;17(6):1595–1612.
7. Embuscado ME. Spices and herbs: natural sources of antioxidants – a mini review. J Funct Foods. 2015;18:811–819.
8. Barbosa-Cánovas GV, Juliano P, Peleg M. Engineering approaches to improving food quality and safety. J Food Eng. 2014;123:1–3.
9. Sila A, Bougatef A. Antioxidant peptides from marine by-products: isolation, identification and application in food systems. A review. J Funct Foods. 2016;21:10–26.
10. Ngo D-H, Vo TS, Ngo DN, Wijesekara I, Kim SK. Biological activities and potential health benefits of bioactive peptides derived from marine organisms. Int J Biol Macromol. 2012;51(4):378–383.
11. Harnedy PA, FitzGerald RJ. Bioactive peptides from marine processing waste and shellfish: a review. J Funct Foods. 2012;4(1):6–24.
12. Calder PC. Omega-3 fatty acids and inflammatory processes: from molecules to man. Biochem Soc Trans. 2017;45(5):1105–1115.
13. Lafarga T, Hayes M. Bioactive peptides from food proteins: mineral binding and bioavailability. Curr Opin Food Sci. 2016;8:28–34.
14. Swanson D, Block R, Mousa SA. Omega-3 fatty acids EPA and DHA: health benefits throughout life. Adv Nutr. 2012;3(1):1–7.
15. Abdelhamid AS, Brown TJ, Brainard JS, Biswas P, Thorpe GC, Moore HJ, et al. Omega-3 fatty acids for the primary and secondary prevention of cardiovascular disease. Cochrane Database Syst Rev. 2020;3:CD003177.
16. EFSA Panel on Dietetic Products, Nutrition and Allergies (NDA). Scientific opinion on dietary reference values for vitamin A. EFSA J. 2015;13(3):4028.
17. EFSA Panel on Dietetic Products, Nutrition and Allergies (NDA). Scientific opinion on dietary reference values for vitamin B6 and vitamin B12. EFSA J. 2016;14(6):4482.
18. EFSA Panel on Dietetic Products, Nutrition and Allergies (NDA). Scientific opinion on dietary reference values for selenium. EFSA J. 2014;12(10):3846.
19. Olafsdóttir G, Lauzon HL, Martinsdóttir E, Kristbergsson K. Evaluation of shelf life of fish by quality index method (QIM). J Food Sci. 2010;70(6):S401–S407.
20. Leygonie C, Britz TJ, Hoffman LC. Impact of freezing and thawing on the quality of meat: review. Meat Sci. 2012;91(2):93–98.
21. Duranton F, Simonin H, Guyon C, Chevalier D, Roux P, De Lamballerie M. Combined use of salt replacers and high-pressure treatment to preserve the quality of cooked ham. Innov Food Sci Emerg Technol. 2014;23:84–91.
22. Mujumdar AS, Law CL. Drying technology: trends and applications in postharvest processing. Food Bioprocess Technol. 2010;3(6):843–852.

23. Guillen MD, Errecalde MC, Salmerón J, Casas C. Headspace volatile components of smoked swordfish (Xiphias gladius) and cod (Gadus morhua). J Sci Food Agric. 2009;89(6):913–920.
24. Alomirah H, Al-Zenki S, Al-Hooti S, Zaghloul S, Sawaya W, Ahmed N, et al. Concentrations and dietary exposure to polycyclic aromatic hydrocarbons (PAHs) from grilled and smoked foods. Food Control. 2011;22(12):2028–2035.
25. Burt S. Essential oils: their antibacterial properties and potential applications in foods—a review. Int J Food Microbiol. 2009;94(3):223–253.
26. Hyldgaard M, Mygind T, Meyer RL. Essential oils in food preservation: mode of action, synergies, and interactions with food matrix components. Front Microbiol. 2012;3:12.
27. Tongnuanchan P, Benjakul S. Essential oils: extraction, bioactivities, and their uses for food preservation. J Food Sci. 2014;79(7):R1231–R1249.
28. Kumar MNVR. A review of chitin and chitosan applications. React Funct Polym. 2009;69(9):636–656.
29. Alishahi A, Aïder M. Applications of chitosan in the seafood industry and aquaculture: a review. Food Bioprocess Technol. 2012;5(3):817–830.
30. Mani-López E, García HS, López-Malo A. Organic acids as antimicrobials to control Salmonella in meat and poultry products. Food Res Int. 2012;45(2):713–721.
31. Gálvez A, Abriouel H, López RL, Ben Omar N. Bacteriocin-based strategies for food preservation. Int J Food Microbiol. 2010;120(1-2):51–70.
32. Kim SK, Wijesekara I. Development and biological activities of marine-derived bioactive peptides: a review. J Funct Foods. 2010;2(1):1–9.
33. He S, Franco C, Zhang W. Fish protein hydrolysates: application in deep-fried food and potential antioxidative activity. J Food Sci. 2011;76(3):C428–C437.
34. Campus M. High pressure processing of meat, meat products and seafood. Food Eng Rev. 2010;2:256–273.
35. Martínez-Monzó J, Ayala R, Toldrá F. Effect of high pressure on seafood. Food Rev Int. 2013;29(4):308–328.
36. Yagiz Y, Kristinsson HG, Balaban MO, Marshall MR. Effect of high pressure processing on the quality of Atlantic salmon. Food Chem. 2009;116(3):828–835.
37. Toepfl S, Heinz V, Knorr D. Applications of pulsed electric fields technology for the food industry. Food Eng Rev. 2010;2:147–156.
38. Guerrero-Beltrán JA, Barbosa-Cánovas GV. Advantages and limitations on processing foods by UV light. Food Sci Technol Int. 2009;10(3):137–147.
39. Pandiselvam R, Subhashini S, Banuu Priya EP, Kothakota A, Ramesh SV, Shahir S. Ozone based food preservation: a promising green technology for enhanced food safety. Ozone: Sci Eng. 2017;39(2):93–109.
40. Parlapani FF, Mallouchos A, Haroutounian SA, Boziaris IS. Microbiological spoilage and volatiles of modified atmosphere packaged Mediterranean fish. Food Microbiol. 2014;39:19–31.
41. Carocho M, Morales P, Ferreira ICFR. Natural food additives: Quo vadis? Trends Food Sci Technol. 2015;45(2):284–295.
42. Asioli D, Aschemann-Witzel J, Caputo V, Vecchio R, Annunziata A, Næs T, Varela P. Making sense of the "clean label" trends: a review of consumer food choice behavior and discussion of industry implications. Food Res Int. 2017;99:58–71.
43. Majumdar RK, Basu S, Nayak BB, Pal J, Rahman A. Technology for improving quality of fishery products from catch to consumer. Fish Technol. 2016;53(2):85–96.