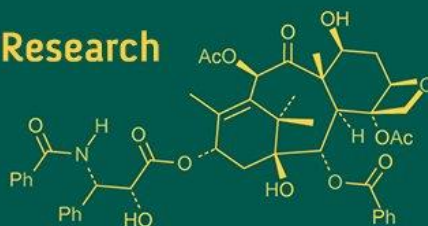


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693

ISSN Online: 2617-4707

NAAS Rating (2026): 5.29

IJABR 2026; 10(7): 11-17

www.biochemjournal.com

Received: 12-04-2026

Accepted: 16-05-2026

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Recent advances technology for shelf-life enhancement of fisheries products

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i7a.8916>

Abstract

Fish and fishery products are highly perishable commodities because of their high moisture content, neutral pH, autolytic enzyme activity, unsaturated lipid content, and rapid microbial proliferation after harvest. These factors result in fast quality deterioration, leading to economic losses, reduced market value, and concerns regarding food safety. In recent years, considerable progress has been made in the development of advanced preservation technologies aimed at extending the shelf life of fisheries products while maintaining their nutritional and sensory quality. This review summarizes recent advances in shelf-life enhancement technologies for fish and fishery products, with emphasis on cold preservation methods such as superchilling, slurry ice, cryogenic freezing, and refrigerated storage; non-thermal processing technologies including high-pressure processing, pulsed electric field, cold plasma, and ultraviolet treatment; and advanced packaging systems such as vacuum packaging, modified atmosphere packaging, and active and intelligent packaging. The review also highlights the growing application of edible coatings, chitosan-based films, plant extracts, essential oils, and natural antioxidants as eco-friendly preservation approaches. In addition, important quality assessment tools and shelf-life evaluation methods, including sensory, microbiological, chemical, and instrumental indicators, are discussed in relation to modern preservation strategies. Although these technologies offer significant potential to reduce spoilage and improve storage stability, challenges remain in terms of cost, process optimization, industrial scalability, regulatory acceptance, and maintaining product quality under commercial conditions. Future research should focus on integrated hurdle approaches, sustainable packaging materials, real-time freshness monitoring, and the development of efficient, consumer-acceptable, and environmentally friendly preservation systems.

Keywords: Fishery products, shelf-life, cold preservation, non-thermal processing

1. Introduction

Fisheries products are among the most nutritious foods because they provide high-quality protein, essential amino acids, vitamins, minerals, and health-promoting omega-3 fatty acids. However, fish and shellfish are highly perishable commodities due to their high moisture content, neutral pH, autolytic enzyme activity, unsaturated lipids, and rapid microbial growth after harvest. As a result, deterioration in texture, flavor, color, and nutritional quality occurs quickly, leading to reduced market value and considerable post-harvest losses. Therefore, extending the shelf-life of fisheries products has become a major focus of modern fish processing and preservation research. (Kontominas *et al.*, 2021) ^[12, 13]

In recent years, significant advances have been made in technologies aimed at maintaining the freshness, safety, and overall quality of fisheries products during storage and distribution. Conventional preservation methods such as icing, chilling, freezing, drying, salting, and smoking are now being complemented by advanced approaches including superchilling, modified atmosphere packaging (MAP), vacuum packaging, active and intelligent packaging, edible coatings, and natural bio-preservatives. In addition, emerging non-thermal technologies such as high-pressure processing (HPP), pulsed electric field (PEF), cold plasma, ultraviolet treatment, and ozone application have shown promising potential for controlling microbial spoilage and slowing biochemical deterioration while preserving the fresh-like characteristics of seafood. (Yu *et al.*, 2020; Russo *et al.*, 2024) ^[36, 27]

Another important trend in shelf-life enhancement is the development of edible films and coatings, nano-engineered packaging materials, and bioactive compounds of natural origin.

These innovations not only inhibit microbial growth and lipid oxidation but also support the growing demand for sustainable, safe, and minimally processed seafood products. Thus, recent advances in fisheries preservation technology are increasingly focused on combining quality retention, food safety, environmental sustainability, and consumer acceptance. This topic therefore highlights the modern technologies that are transforming fisheries product preservation and improving shelf-life in both fresh and processed seafood. (Kurek *et al.*, 2024; Cetinkaya and Wijaya, 2024) ^[14, 3].

2. Causes of Spoilage in Fisheries Products

Fisheries products are among the most perishable foods because their muscle contains high moisture (generally around 75-80%), abundant soluble nitrogenous compounds, relatively low connective tissue, and a near-neutral post-mortem pH, all of which favor rapid biochemical and microbial deterioration. The literature consistently groups fish spoilage into three major mechanisms: autolytic enzymatic spoilage, microbial spoilage, and oxidative spoilage. These mechanisms do not act independently; rather, they proceed simultaneously after harvest and together reduce freshness, safety, sensory acceptability, and shelf-life of fish and shellfish products. In addition, the rate of spoilage is strongly influenced by species, fat content, handling practices, sanitation, storage temperature, and packaging conditions. (Kontominas *et al.*, 2021) ^[12, 13].

2.1 Autolytic enzymatic spoilage

Autolytic spoilage begins immediately after the death of the fish due to the action of endogenous enzymes naturally present in the muscle and viscera. Once circulation stops, oxygen supply ceases and the muscle shifts to anaerobic metabolism, resulting in ATP depletion, lactic acid accumulation, rigor mortis, and subsequent softening of the flesh. Proteolytic enzymes such as cathepsins, calpains, collagenases, trypsin-like enzymes, and other muscle proteases hydrolyze structural proteins and connective tissue components, causing loss of firmness, gaping, drip loss, and texture deterioration. Enzymatic hydrolysis also releases peptides, amino acids, and other low-molecular-weight compounds that can later serve as substrates for spoilage microorganisms. Although autolysis alone may not always generate the strong off-odours associated with spoiled fish, it significantly lowers quality by accelerating softening, belly bursting, color changes, and overall loss of freshness, especially in inadequately chilled products (Tavares *et al.*, 2021) ^[29].

2.2 Microbial spoilage

Among all spoilage pathways, microbial growth is generally considered the major cause of quality loss in fresh and lightly preserved fisheries products. Fish surfaces, gills, and intestines naturally carry microorganisms from the aquatic environment, and additional contamination may occur during harvesting, washing, handling, icing, transport, processing, and storage. After death, the defense system of the fish is lost and spoilage bacteria proliferate rapidly, particularly under chilled conditions if temperature control is poor. Several studies have identified specific spoilage organisms (SSOs) responsible for sensory rejection of seafood, especially psychrotrophic Gram-negative bacteria such as *Pseudomonas spp.*, *Shewanella putrefaciens*,

Photobacterium phosphoreum, *Aeromonas spp.*, *Vibrio spp.*, *Acinetobacter*, and *Moraxella*. Their dominance depends on the fish species, water source, oxygen availability, salt level, and packaging system. For example, *Pseudomonas* and *Shewanella* are commonly associated with aerobically stored chilled fish, whereas *Photobacterium phosphoreum* becomes important in CO₂-rich modified-atmosphere storage (Gram and Huss, 1996) ^[9]. Microbial spoilage results from the metabolism of fish proteins, amino acids, trimethylamine oxide (TMAO), and other nitrogenous compounds. Spoilage bacteria produce volatile and malodorous metabolites such as trimethylamine (TMA), total volatile basic nitrogen (TVB-N), ammonia, hydrogen sulfide, sulfides, aldehydes, ketones, alcohols, organic acids, and biogenic amines including histamine, cadaverine, and putrescine. These compounds are responsible for the typical off-odours, sour or ammonia-like smell, slime formation, discoloration, and unacceptable taste of spoiled seafood. In marine fish, reduction of TMAO to TMA by bacteria such as *Shewanella* and *Photobacterium* is a key spoilage reaction and is widely used as an indicator of quality deterioration. Therefore, microbial spoilage not only shortens shelf-life but may also create food safety concerns when toxin-forming or pathogenic bacteria are present (Wang *et al.*, 2026) ^[32].

2.3 Oxidative spoilage

Oxidative spoilage is another major cause of deterioration, particularly in fatty and pelagic fish species such as sardine, mackerel, tuna, and herring, which are rich in polyunsaturated fatty acids. Fish lipids are highly susceptible to oxidation because they contain large amounts of long-chain omega-3 fatty acids, and these unsaturated lipids react readily with oxygen during handling and storage. Lipid oxidation may occur through auto-oxidation, photo-oxidation, thermal oxidation, or enzyme-mediated oxidation. The process initially forms hydroperoxides, which then break down into secondary products such as aldehydes, ketones, and other carbonyl compounds. These products cause rancid odour, off-flavour, discoloration, loss of nutritional quality, and changes in texture and water-holding capacity. Oxidation can also destroy fat-soluble vitamins and essential fatty acids, thereby reducing the nutritional value of fish products. The problem becomes more severe when fish are exposed to oxygen, light, high temperature fluctuations, metal catalysts, or repeated freezing and thawing. (Wang, and Zheng, 2025) ^[33].

2.4 Role of intrinsic and extrinsic factors in spoilage

The literature shows that spoilage intensity is not determined by one factor alone but by the interaction of intrinsic product properties and external storage conditions. Intrinsic factors include species, size, biochemical composition, pH, water activity, fat content, and the natural microbial flora associated with skin, gills, and gut. Extrinsic factors include harvesting method, stress before death, delay in icing, storage temperature, hygiene during handling, cross-contamination from water or equipment, packaging atmosphere, and duration of storage. High temperatures accelerate enzymatic reactions, microbial growth, and oxidation, while poor sanitation increases the initial microbial load and shortens the lag phase of spoilage organisms. Similarly, inadequate cold chain maintenance during transport and marketing can rapidly convert fresh

fish into unacceptable products. Thus, understanding the causes of spoilage requires a combined view of biochemical, microbiological, and environmental factors affecting fisheries products after harvest (Mafe *et al.*, 2024) ^[16].

3. Importance of Shelf-Life Enhancement in Fisheries Products

Shelf-life enhancement is highly important in fisheries products because fish and shellfish are among the most perishable foods. Their high moisture content, near-neutral pH, abundance of non-protein nitrogen compounds, and high level of unsaturated fatty acids make them highly susceptible to microbial spoilage, enzymatic autolysis, and lipid oxidation soon after harvest. Therefore, extending shelf-life is essential to slow quality deterioration and preserve the freshness, texture, flavor, and nutritional value of seafood during storage and distribution (Amara *et al.*, 2021) ^[2]. Improving shelf-life is also crucial for maintaining food safety and reducing post-harvest losses. Preservation methods such as icing, chilling, modified atmosphere packaging, edible coatings, and active packaging help inhibit spoilage microorganisms and delay biochemical changes, thereby keeping fishery products acceptable and safe for a longer period. This is especially important because seafood often passes through long marketing chains, and any delay in processing or transport can lead to serious economic losses. Shelf-life extension therefore supports better utilization of fish resources, reduces waste, and increases profitability for the fisheries sector (Karnwal *et al.*, 2025) ^[11]. In addition, shelf-life enhancement has great significance from a nutritional and consumer perspective. Fisheries products are rich in high-quality proteins, essential amino acids, vitamins, minerals, and omega-3 fatty acids, but these nutrients can deteriorate rapidly if preservation is inadequate. By extending shelf-life, the nutritional quality and sensory acceptability of seafood can be retained for a longer time, ensuring consumer satisfaction and improving marketability in both domestic and export trade. Thus, shelf-life enhancement plays a key role in ensuring quality, safety, economic value, and sustainability of fisheries products (Ali *et al.*, 2022) ^[1].

4. Recent Cold Preservation Technologies

4.1 Super chilling

Superchilling is a recent cold preservation technology in which fish or fishery products are stored at about 1-2 °C below their initial freezing point, usually around -1 to -2.5 °C, so that only a small portion of water in the muscle freezes. This partial ice formation slows microbial growth, enzymatic activity, and biochemical spoilage more effectively than ordinary chilling, while still maintaining a fresh-like appearance and quality. Because of this, superchilling is considered an intermediate method between chilling and freezing for extending the shelf life of seafood (Wu *et al.*, 2014) ^[34]. Eliasson *et al.* (2019) ^[6] reported that superchilling can extend fish shelf life by about 1.4-5 times compared with conventional chilled storage, depending on species and storage conditions. It also helps reduce spoilage indicators such as total viable count, TVB-N, and sensory deterioration, although poor temperature control may lead to ice recrystallization, drip loss, and texture damage. Recent research has further shown that combining superchilling with technologies such as modified atmosphere packaging

(MAP) can improve microbial stability and quality retention in high-value fish products, making superchilling one of the most promising modern cold preservation approaches in fisheries. (Mei *et al.*, 2020) ^[17]

4.2 Slurry ice

Slurry ice is a modern cold preservation technology consisting of a suspension of fine spherical ice crystals in water or seawater, generally maintained at subzero temperatures close to -1 to -2 °C. Unlike conventional flake ice, slurry ice has high fluidity and excellent heat-transfer capacity, allowing it to surround fish or shellfish completely and cool them rapidly and uniformly. Because of its small, smooth ice particles, it causes less mechanical damage to the product surface than crushed or flake ice. This rapid and gentle chilling slows microbial growth, enzymatic activity, lipid oxidation, and nucleotide degradation, thereby preserving freshness and sensory quality more effectively than traditional icing methods (Zheng *et al.*, 2026) ^[37, 38]. Recent studies show that slurry ice can significantly improve the shelf life and quality of aquatic products during storage and transport. It has been reported to maintain better texture, appearance, and biochemical quality in fish and shrimp, while lowering spoilage indicators such as total volatile basic nitrogen (TVB-N), trimethylamine (TMA), and microbial counts compared with flake ice storage. For example, studies on turbot, shrimp, and Bombay duck demonstrated that slurry ice delayed sensory deterioration and reduced oxidation and bacterial growth. Owing to these advantages, slurry ice is now regarded as one of the most promising recent cold preservation technologies for fishery products, particularly in modern seafood cold-chain logistics and onboard chilling systems (Rodríguez *et al.*, 2006; Liu *et al.*, 2023) ^[25, 15]

4.3 Cryogenic freezing

Cryogenic freezing is an advanced cold preservation technology in which fish or fishery products are frozen extremely rapidly using cryogenic refrigerants such as liquid nitrogen (-196 °C) or liquid carbon dioxide. Unlike conventional air or plate freezing, cryogenic freezing removes heat very quickly, allowing the product to pass rapidly through the critical zone of maximum ice crystal formation. This leads to the development of smaller and more uniformly distributed ice crystals, which minimizes cellular damage, drip loss, texture softening, and nutrient deterioration during frozen storage and thawing. As a result, cryogenic freezing is highly effective for preserving the freshness, texture, color, water-holding capacity, and sensory quality of high-value aquatic products such as fish fillets, shrimp, shellfish, and surimi-based products. Recent studies also show that liquid nitrogen quick-freezing can better maintain protein stability and reduce oxidation compared with conventional freezing methods, thereby improving the shelf life and market quality of seafood. However, the technology is relatively expensive because of the cost of cryogenic refrigerants and specialized equipment, which may limit its wider commercial use. Nevertheless, due to its ultra-fast freezing rate and superior quality retention, cryogenic freezing is regarded as one of the most promising recent cold preservation technologies for fisheries products (Nateras-Ramírez *et al.*, 2026; Zheng *et al.*, 2026) ^[21, 37, 38].

5. Non-Thermal Processing Technologies

5.1 High Pressure Processing (HPP)

High Pressure Processing (HPP), also known as high hydrostatic pressure processing, is an important non-thermal preservation technology used to improve the safety and shelf life of fish and fishery products without the severe quality losses associated with heat treatment. In this method, packaged seafood is subjected to very high pressure, generally in the range of 100-600 MPa (and sometimes higher), for a short period using water as the pressure-transmitting medium. Because pressure is applied uniformly and instantaneously throughout the product, HPP can inactivate spoilage microorganisms, foodborne pathogens, and some endogenous enzymes while largely retaining the fresh-like sensory and nutritional quality of seafood. It is therefore considered a form of “cold pasteurization” suitable for value-added and minimally processed fish products. HPP has been reported to extend the refrigerated shelf life of seafood, improve microbial safety, and in shellfish it can also assist in shucking and meat recovery. However, the effectiveness of HPP depends on pressure level, holding time, temperature, fish species, and product composition, and excessive pressure may cause changes in texture, color, protein denaturation, and lipid oxidation in some products. Overall, HPP is regarded as one of the most promising recent non-thermal technologies for seafood preservation because it offers an effective balance between microbial safety, shelf-life extension, and quality retention (Roobab *et al.*, 2022; Ali *et al.*, 2022) ^[26, 1].

5.2 Pulsed Electric Field (PEF)

Pulsed Electric Field (PEF) is an emerging non-thermal processing technology used to improve the safety, shelf life, and quality of fish and fishery products with minimal heating. In this method, seafood is exposed to short pulses of high-voltage electric fields, generally in the range of 0.1-80 kV/cm for microseconds to milliseconds, causing electroporation of microbial and cellular membranes. This membrane disruption helps inactivate spoilage microorganisms and some enzymes, while also enhancing mass transfer processes such as salting, marination, drying, and extraction of valuable bioactive compounds from fish by-products. Compared with conventional thermal treatments, PEF better preserves the fresh-like characteristics of seafood, including texture, color, flavour, and nutritional quality, because the temperature rise during treatment is limited. Recent studies indicate that PEF has promising applications in seafood preservation, tenderization, shucking, dehydration, and by-product valorization, making it a versatile technology for modern fish processing. However, its effectiveness depends on factors such as electric field strength, pulse duration, product conductivity, and fish tissue structure, and industrial application in seafood is still limited by high equipment cost and process optimization challenges (Ekonomou and Bozaris, 2021; Gómez *et al.*, 2019) ^[5, 8].

5.3 Cold plasma

Cold plasma (CP) is an emerging non-thermal processing technology used to improve the safety and shelf life of fish and fishery products without exposing them to severe heat. It is generated by applying energy to gases such as air, oxygen, nitrogen, or argon, producing a mixture of reactive

oxygen and nitrogen species, charged particles, UV photons, and free radicals at near-ambient temperature. These reactive species inactivate spoilage microorganisms and foodborne pathogens mainly by damaging cell membranes, proteins, and nucleic acids, thereby reducing microbial load on seafood surfaces and packaging materials. Because the treatment operates at low temperature, cold plasma can preserve the fresh-like characteristics of seafood better than conventional thermal methods, with relatively less impact on flavour, texture, and nutritional quality (Olatunde *et al.*, 2021; Punia Bangar *et al.*, 2022) ^[22, 24]. Recent studies have shown that cold plasma has promising applications in seafood preservation, including surface decontamination, extension of refrigerated shelf life, packaging sterilization, and improvement of microbial safety in fish fillets, shrimp, shellfish, and ready-to-eat seafood products. It is particularly attractive as a hurdle technology because it can be combined with refrigeration, modified atmosphere packaging, or other non-thermal methods for greater preservation efficiency. However, the effectiveness of cold plasma depends on treatment conditions such as gas composition, voltage, exposure time, product surface characteristics, and moisture content. Excessive treatment may also promote lipid oxidation, protein oxidation, discoloration, or textural changes in some fatty seafood products. Nevertheless, due to its strong antimicrobial action, low thermal damage, and growing potential in seafood processing, cold plasma is regarded as one of the most promising recent non-thermal preservation technologies for fish and fishery products (Punia Bangar *et al.*, 2022) ^[24].

5.4 UV treatment

Ultraviolet (UV) treatment, particularly UV-C irradiation (200-280 nm; commonly around 254 nm), is an important non-thermal preservation technology used to improve the microbial safety and shelf life of fish and fishery products. UV-C acts mainly by damaging microbial DNA and RNA through the formation of pyrimidine dimers, thereby inhibiting replication and leading to inactivation of spoilage microorganisms and foodborne pathogens. Because it is a non-thermal surface treatment, UV-C can reduce microbial load with minimal heating, helping preserve the fresh-like sensory and nutritional quality of seafood compared with conventional thermal processing. In seafood systems, UV treatment has been investigated for fish fillets, shrimp, shellfish, and processing surfaces, where it can delay spoilage and extend refrigerated shelf life when appropriate doses are applied. However, its antimicrobial effect is largely limited to the product surface because of the low penetration power of UV light, and excessive exposure may accelerate lipid oxidation, discoloration, protein changes, and texture deterioration, especially in fatty fish. Therefore, recent research increasingly recommends combining UV-C with hurdle approaches such as vacuum packaging, oxygen absorbers, refrigeration, or other non-thermal technologies to improve preservation efficiency while minimizing quality loss. Overall, UV treatment is regarded as a promising, low-cost and environmentally friendly non-thermal technology for seafood preservation, particularly for surface decontamination and shelf-life extension of minimally processed fish products. (Monteiro *et al.*, 2021; Monteiro *et al.*, 2023) ^[20, 19]

6. Advanced Packaging Technologies

6.1 Vacuum Packaging

Vacuum packaging is one of the simplest and most widely used advanced packaging technologies for seafood preservation. In this method, air is removed from the package before sealing, thereby reducing oxygen levels and slowing oxidative rancidity, discoloration, and the growth of aerobic spoilage microorganisms. In fish and shellfish, vacuum packaging helps preserve freshness, texture, and flavour while reducing drip loss and extending refrigerated shelf life compared with aerobic storage. It is particularly useful for fresh fillets, smoked fish, cooked shrimp, and value-added seafood products. However, because oxygen is largely absent, vacuum packaging may favour the growth of anaerobic or facultative anaerobic bacteria if temperature control is poor; therefore, strict refrigeration and hygienic handling are essential. Overall, vacuum packaging is considered an economical and effective method for improving the storage stability of fishery products ((DeWitt and Oliveira, 2016)^[4].

6.2 Modified Atmosphere Packaging (MAP)

Modified atmosphere packaging (MAP) is a more advanced system in which the gaseous atmosphere inside the package is replaced with selected gases such as carbon dioxide (CO₂), nitrogen (N₂), and oxygen (O₂) in proportions suited to the product. In seafood preservation, CO₂ is the most important gas because of its bacteriostatic and fungistatic effects, while N₂ is used as an inert filler and O₂ may be included in some products to maintain colour or suppress anaerobic pathogens. MAP significantly slows microbial growth, oxidative spoilage, and biochemical deterioration, and is therefore widely used to extend the shelf life of fresh fish fillets, shellfish, and minimally processed seafood. Shelf-life improvement under MAP depends on fish species, fat content, gas composition, gas-to-product ratio, packaging film permeability, and storage temperature. When combined with superchilling or proper cold-chain management, MAP can markedly improve the quality and marketability of fishery products. Nevertheless, improper gas mixtures or temperature abuse may allow the growth of psychrotrophic pathogens such as *Clostridium botulinum*, making refrigeration control essential (DeWitt and Oliveira, 2016; Sivertsvik *et al.*, 2002)^[4, 28].

6.3 Active and Intelligent Packaging

Active and intelligent packaging represents the most recent advancement in seafood packaging technology. Active packaging goes beyond passive containment by incorporating components that interact with the product or package environment to enhance shelf life and safety. Common active systems for fishery products include oxygen scavengers, carbon dioxide emitters/absorbers, moisture absorbers, antimicrobial films, antioxidant-releasing films, and ethylene or odour absorbers. These systems help control oxidation, microbial growth, moisture accumulation, and undesirable odours, thereby improving the quality and shelf life of fish and shellfish. Intelligent packaging, in contrast, is designed to monitor and communicate product condition rather than directly preserve it. Examples include time-temperature indicators, freshness indicators, gas sensors, RFID-based traceability tools, and biosensors that can signal temperature abuse, microbial spoilage, or package leakage. In fishery products, intelligent packaging is particularly

valuable because seafood is highly perishable and quality can deteriorate rapidly if cold-chain conditions are not maintained. Together, active and intelligent packaging technologies are increasingly regarded as key tools for modern seafood preservation, quality assurance, and smart cold-chain management (Mohan *et al.*, 2025)^[18].

7. Edible Coatings and Natural Preservatives

7.1 Chitosan coatings

Chitosan is one of the most widely studied edible coatings for fish and fishery products because it combines film-forming ability, biodegradability, antimicrobial activity, and antioxidant potential. It is a deacetylated derivative of chitin obtained mainly from crustacean shell waste and can be applied to seafood as a coating, film, dipping solution, or nanoemulsion-based layer. In fish preservation, chitosan coatings act as a semipermeable barrier that reduces oxygen transfer, moisture loss, and surface contamination, while also inhibiting spoilage bacteria through interactions with microbial cell membranes. As a result, chitosan treatment has been reported to retard microbial growth, reduce lipid oxidation, delay protein degradation, and maintain texture and sensory quality in fish fillets, shrimp, and other seafood products during chilled storage. Recent work has further focused on chitosan nanoemulsions and composite coatings incorporating plant extracts or essential oils, which improve coating uniformity and strengthen antimicrobial and antioxidant efficacy compared with chitosan alone. Thus, chitosan coatings are increasingly recognized as an effective clean-label strategy for shelf-life extension of seafood (Yu *et al.*, 2019; Ubaidillah *et al.*, 2026)^[36, 30].

7.2 Plant extracts and essential oils

Plant extracts and essential oils are important natural preservatives in seafood systems because they contain bioactive compounds such as phenolics, flavonoids, terpenes, aldehydes, and organic acids that exhibit both antimicrobial and antioxidant properties. Extracts from clove, oregano, thyme, rosemary, cinnamon, garlic, green tea, pomegranate peel, grape seed, and various herbs and spices have been applied to fish and shellfish as dipping solutions, edible coatings, marinades, and active packaging components. These natural compounds can inhibit spoilage microorganisms, suppress lipid oxidation, delay off-odour formation, and preserve colour and texture during storage. Essential oils are particularly effective because of their volatile hydrophobic constituents, which disrupt microbial cell membranes and interfere with cellular metabolism. However, their direct use may be limited by strong aroma, volatility, and uneven dispersion in aqueous foods. To overcome these problems, recent research increasingly combines plant extracts or essential oils with chitosan-based coatings, nanoemulsions, or encapsulation systems, which improve stability, controlled release, and preservative efficiency while minimizing adverse sensory effects. Therefore, plant-derived preservatives are now considered promising alternatives to synthetic additives for maintaining seafood quality and safety (Hussain *et al.*, 2021; Venkatachalam *et al.*, 2025)^[10, 31].

7.3 Natural antioxidants

Natural antioxidants are used in fish and fishery products mainly to control lipid oxidation, pigment deterioration, protein oxidation, and flavour loss, which are major causes

of quality decline in fatty and minimally processed seafood. These antioxidants are commonly derived from plant extracts, essential oils, algae, spices, fruits, vegetables, and bioactive peptides, and include compounds such as polyphenols, carotenoids, tocopherols, ascorbic acid, flavonoids, and phenolic acids. In seafood preservation, natural antioxidants function by scavenging free radicals, chelating pro-oxidant metals, interrupting oxidation chain reactions, and stabilizing cell membranes and pigments. Their incorporation into edible coatings, ice systems, marinades, and active packaging has been shown to reduce peroxide formation, thiobarbituric acid reactive substances (TBARS), and other spoilage indicators, thereby extending shelf life and preserving nutritional quality. Recent studies emphasize that natural antioxidants are most effective when used as part of a hurdle approach, for example in combination with chitosan coatings, vacuum or modified atmosphere packaging, or chilled storage. Such combinations not only retard oxidative rancidity but also help suppress microbial spoilage, making natural antioxidants an increasingly important component of modern sustainable seafood preservation strategies (Pandiyani *et al.*, 2025; Hussain *et al.*, 2021) ^[23, 10].

8. Challenges and Future Prospects

Despite major advances in seafood preservation, several challenges still limit the large-scale adoption of modern technologies. Fish and fishery products are highly perishable, and no single preservation method can completely control microbial spoilage, lipid oxidation, enzymatic autolysis, moisture loss, and texture deterioration at the same time. Many emerging technologies such as high-pressure processing, pulsed electric field, cold plasma, superchilling, cryogenic freezing, and smart packaging show strong potential for shelf-life extension, but their effectiveness often depends on fish species, fat content, product form, packaging system, and strict cold-chain management. In addition, some techniques may cause undesirable quality changes, including protein denaturation, colour alteration, drip loss, oxidation, or textural softening if processing conditions are not optimized. High equipment cost, energy demand, process standardization, limited industrial-scale validation, and regulatory acceptance are further constraints, especially for small-and medium-scale seafood processors. Future prospects in seafood preservation are therefore moving toward integrated or hurdle-based preservation systems that combine multiple mild technologies to achieve better safety and quality retention with fewer side effects. Examples include combining superchilling with modified atmosphere packaging, chitosan or edible coatings with plant extracts and essential oils, or non-thermal processing with active/intelligent packaging. Another major trend is the development of green and sustainable preservation approaches, including biodegradable packaging materials, bio-based coatings, natural preservatives, and the valorization of seafood by-products for antimicrobial and antioxidant applications. At the same time, rapid quality-monitoring tools such as biosensors, freshness indicators, hyperspectral imaging, and AI-assisted shelf-life prediction are expected to strengthen real-time quality control across the seafood cold chain. Overall, future research should focus on process optimization, scale-up, techno-economic feasibility, consumer acceptance, and regulatory harmonization so that

advanced preservation technologies can be translated from laboratory studies into commercially viable systems for safer, longer-lasting, and more sustainable fishery products.

9. Conclusion

Fish and fishery products are among the most highly perishable food commodities, making shelf-life enhancement a major priority for the seafood industry. Recent advances in preservation technologies have significantly improved the ability to maintain the freshness, safety, nutritional value, and market quality of fisheries products during storage and distribution. Modern cold preservation methods such as superchilling, slurry ice, and cryogenic freezing have shown considerable promise in slowing microbial growth, enzymatic activity, and biochemical deterioration while preserving fresh-like quality. Similarly, non-thermal processing technologies including high-pressure processing, pulsed electric field, cold plasma, and ultraviolet treatment offer effective alternatives to conventional heat-based preservation by enhancing microbial safety with minimal adverse effects on sensory and nutritional attributes. In addition to these approaches, advanced packaging systems such as vacuum packaging, modified atmosphere packaging, active packaging, and intelligent packaging have further strengthened seafood preservation by improving product stability and enabling better monitoring of quality changes during storage. The use of edible coatings, chitosan-based films, plant extracts, essential oils, and natural antioxidants has also emerged as a sustainable and eco-friendly strategy for controlling oxidation and microbial spoilage. Furthermore, the integration of modern quality assessment tools, including sensory, microbiological, chemical, and rapid instrumental techniques, has improved the accuracy of shelf-life evaluation and quality control in fishery products.

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