

Vacuum Packaging of Fish and Fishery Products: Principles, Quality Preservation, Shelf-Life Extension, Safety Aspects and Future Perspectives

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Abstract

Fish and fishery products are highly nutritious but extremely perishable because of their high moisture content, neutral pH, unsaturated fatty acids and rapid microbial activity. As a result, significant post-harvest losses occur during storage, transport and marketing, especially in developing countries. Packaging plays a vital role in maintaining fish quality and safety and among modern techniques, vacuum packaging has emerged as an effective and practical solution. Vacuum packaging works by removing air from the package, thereby reducing oxygen availability, slowing microbial growth and minimizing oxidative spoilage. This article explains the basic principles of vacuum packaging, commonly used packaging materials and equipment and how vacuum conditions help preserve fish quality. The effects of vacuum packaging on microbial load, lipid oxidation, texture, colour and sensory attributes are discussed. Its applications in fresh, chilled, frozen, smoked, dried and value-added fish products are highlighted with practical examples. Food safety concerns, challenges and future opportunities for sustainable seafood packaging are also briefly addressed.

Keywords: Vacuum packaging, Fish preservation, Shelf life, Lipid oxidation, Microbial quality, Seafood packaging

Introduction

Fish and fishery products are highly nutritious, supplying quality proteins, essential amino acids, omega-3 fatty acids, vitamins and minerals. However, they are highly perishable and rapidly deteriorate after harvest as a result of lipid oxidation, enzymatic autolysis and microbial development, which causes colouring, softening of the texture, smells and nutrient loss (Yadav et al., 2025a: 2025b). Conventional preservation techniques including icing, chilling, freezing, salting and drying helps in delaying spoiling, but they are sometimes insufficient for extensive storage and distribution, particularly when temperatures fluctuate. Packaging is essential to improving preservation. Fish kept in traditional air packaging are exposed to oxygen, which increases up aerobic bacteria development and deterioration. By eliminating air before sealing, vacuum packaging produces an oxygen-depleted environment that inhibits aerobic spoilage organisms and slows oxidative reactions. Both industrial seafood processing and small-scale fisheries use vacuum packaging extensively because of its efficiency, ease of use and accessibility (Rahman et al., 2020: Mehta et al., 2025). Its principles, preservation processes, quality effects, uses, safety considerations and possibilities for the future are all reviewed in this article.

Principle of Vacuum Packaging

The basic principle of vacuum packing is the concept that atmospheric air, especially oxygen, should be removed from the package before it is sealed. Because it stimulates oxidative processes and the growth of aerobic microbes, oxygen is essential to food deterioration. Vacuum packaging extends the shelf life of fish and fish products by removing oxygen, which slows down various spoilage processes (Nasution et al., 2017).

Oxygen Removal and Its Significance

In conventional air packaging, oxygen concentration is approximately 21%, which is sufficient to promote lipid oxidation and microbial proliferation. Vacuum packaging reduces oxygen levels to less than 1%, creating an environment unfavourable for aerobic spoilage bacteria and oxidative reactions. The reduction of oxygen results in:

- Inhibition of aerobic spoilage microorganisms
- Slowing of lipid oxidation and rancidity
- Retardation of pigment oxidation and discoloration
- Reduction in moisture loss and drip formation

Packaging Materials and Equipment Used in Vacuum Packaging

The barrier properties of the packing material, which must include low oxygen permeability, mechanical strength and resistance to moisture and puncture, determine the effectiveness of vacuum packaging is. Multilayer films are frequently utilized, which range from high-barrier materials like PVdC and EVOH-based laminates for the long-term preservation of cooked and processed fish products to barrier materials like PET/LDPE and PA/LDPE for short- to medium-term storage. According to Kontominas et al. (2021), oxygen permeability is normally less than $150 \text{ cm}^3/\text{m}^2 \cdot 24 \text{ h} \cdot \text{atm}$ for PET or PA layers and less than $10 \text{ cm}^3/\text{m}^2 \cdot 24 \text{ h} \cdot \text{atm}$ while PVdC or EVOH is used. PA/PE multilayer films are frequently utilized in commercial fish packaging because PA offers good oxygen barrier qualities while PE assures flexibility and heat sealing.

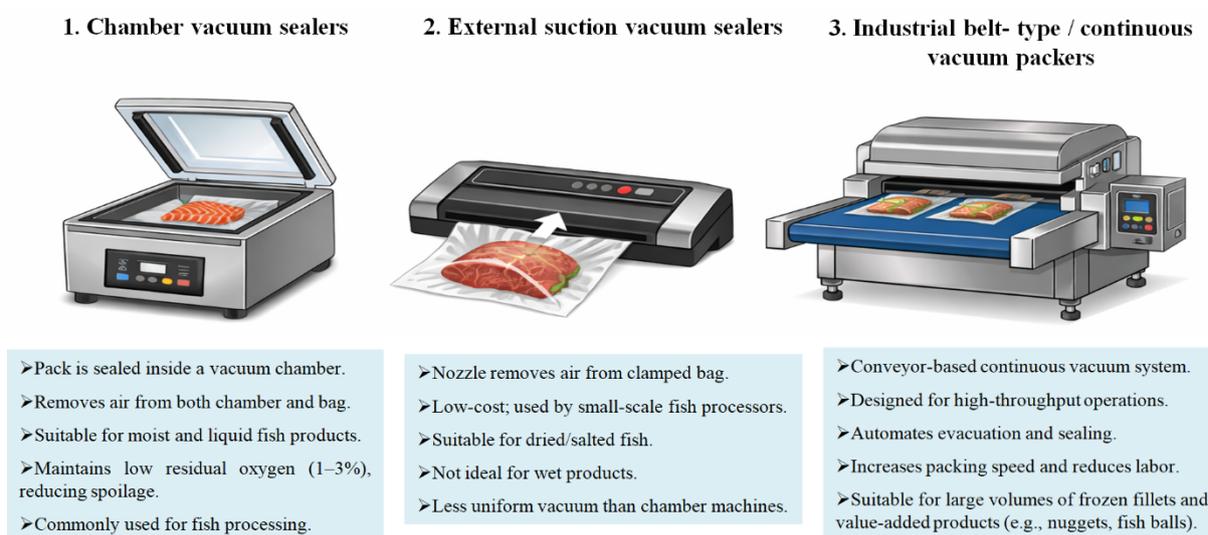


Fig. 1 Equipment used in vacuum packaging

Mechanism of Fish Preservation Under Vacuum Packaging

The preservation effect of vacuum packaging is attributed to several interconnected mechanisms:

Microbial Inhibition: Aerobic spoiling microorganisms, especially *Pseudomonas* species, which predominate in fresh fish stored aerobically, are inhibited by vacuum packaging. It extends shelf life by slowing down protein degradation and lipid oxidation by lowering oxygen levels. While facultative and anaerobic bacteria can thrive in vacuum, they typically proliferate more slowly at the right cold temperatures (Sharma et al., 2023).

Reduction of Lipid Oxidation: Polyunsaturated fatty acids, which are abundant in fish lipids, are very susceptible to oxidative deterioration. By restricting oxygen access, vacuum packaging dramatically lowers lipid oxidation, maintaining nutritional value, flavour, and colour.

Moisture Retention and Texture Preservation: By keeping the fish surface in close contact with the packaging material, vacuum packaging reduces moisture loss and drip production. This minimizes weight loss during storage and helps maintain texture (Patil et al., 2020).

Applications for Vacuum Packaging in Fish and Fishery Products

Fresh Fish: Vacuum packaging extends the refrigerated shelf life of fresh whole fish and fillets by inhibiting microbial growth and oxidative spoilage, outperforming air packaging when paired with temperature control. For instance, vacuum-packed Rohu (*Labeo rohita*) at 4°C lasted 11 days (vs. 8 days in air), with better microbial and biochemical quality (Das et al., 2021). Rainbow trout showed reduced bacteria and lipid oxidation, staying fresh for 7–10 days. Fish fillets at 4°C under vacuum had lower oxidation, drip loss, and better texture/sensory scores over 8 days vs. air (Ramadhan et al., 2025).

Chilled and Frozen Fish: By removing air exposure, vacuum packing protects chilled and frozen fish against freezer burn, dehydration, discolouration and lipid oxidation, which deteriorate texture, taste, and sensory qualities after thawing. It efficiently lowers rancidity and moisture loss. For instance: After 40 days, the levels of peroxide, TBARS, and free fatty acids were lower in frozen *Lethrinus atkinsoni* fillets at -18°C than in air-packed fillets. Compared to less than a month unpackaged, Hilsa at -18°C remained below TBARS limits for over a year (Khatun et al., 2020).

Smoked, Dried and Value-Added Fish Products: Smoked, Dried, and Value-Added Fish Products: By preventing oxygen-induced problems such moisture absorption, lipid oxidation, loss of odour, mold growth, and discoloration, vacuum packing extends the shelf life of smoked, dried, and value-added fish. Compared to 11 days of non-vacuum, smoked mackerel at 4°C retained its taste and texture after 24 days (Maryati et al., 2025). In comparison to air/nitrogen, dried barb at room temperature reached 45 days under vacuum. Compared to air-packed fish balls, value-added fish balls at 4°C acquired around two more weeks of quality with reduced drip loss and degradation (Özpolat, 2022).

Effect of Vacuum Packaging on Fish Quality Attributes

The effectiveness of vacuum packaging in fish preservation is best understood by evaluating its impact on microbiological, chemical, physical and sensory quality attributes. These parameters collectively determine shelf life, safety and consumer acceptability of fish products.

Microbiological Quality

Fresh fish quality degradation is mostly caused by microbial spoiling. Gram-negative aerobic bacteria like *Pseudomonas* spp., *Shewanella putrefaciens*, and *Acinetobacter* spp. are the main causes of spoiling in aerobic storage conditions. These microbes create slime and smells by breaking down nitrogenous substances. When vacuum packaging eliminates oxygen, it suppresses aerobic spoilage bacteria, which drastically changes the microbial ecology of fish. Numerous investigations have shown that, in comparison to their air-packaged counterparts, vacuum-packed fish kept in refrigeration show reduced microbial development. But in a vacuum, facultative anaerobes and lactic acid bacteria might take over. Vacuum packaging does not sterilize the product, even when it delays spoiling. Thus, to guarantee microbiological safety and quality during storage, stringent temperature control is necessary.

Chemical Quality

- **Lipid Oxidation:** Fish lipids are extremely sensitive to oxidation because they are high in polyunsaturated fatty acids. Lipid oxidation results in discoloration, rancid tastes, and nutritional value loss. By reducing oxygen availability, vacuum packaging efficiently lowers lipid oxidation. According to several studies, vacuum-packed fish exhibit substantially lower levels of peroxide and thiobarbituric acid reactive compounds (TBARS) during frozen and refrigerated storage than air-packaged samples.
- **Protein Degradation:** Fish proteins degrade as a result of microbial proteolysis and enzymatic autolysis. By preventing aerobic microbes that produce proteases, vacuum packaging slows down the breakdown of proteins. This leads to less production of volatile basic nitrogen molecules and better texture retention.

Physical and Sensory Quality

- **Texture:** An important quality factor affecting fish's acceptability by consumers is texture. Because vacuum packaging slows enzymatic softening and minimizes moisture loss, it helps retain muscle stiffness. Generally speaking, fish kept in vacuum display greater cohesion and hardness than samples packed in air (Sharma et al., 2024a; 2024b).

- **Color and Appearance:** Fish flesh might turn discolored due to the oxidation of pigments like hemoglobin and myoglobin. By reducing oxygen exposure, vacuum packaging maintains natural color, improving storage appearance.
- **Flavor and Odor:** Vacuum packaging helps preserve desired flavor and odor qualities by minimizing lipid oxidation and microbiological decomposition (Babic Milijasevic et al., 2023).

Shelf-Life Extension of Fish Using Vacuum Packaging

Shelf life is defined as the period during which a food product remains safe and retains acceptable quality attributes. Vacuum packaging has been widely reported to extend the shelf life of fish products by a factor of two to three compared to air packaging, particularly when combined with refrigeration (0–4 °C). The degree of shelf-life extension depends on Fish species, Initial microbial load, Storage temperature, Quality of packaging materials. Vacuum packaging is especially effective when integrated with cold-chain management and good hygienic practices during processing (Mehta et al., 2023).

Sustainability and Environmental Aspects

Modern food systems now prioritize sustainability, especially in fisheries where post-harvest losses are still significant. Mainly by increasing shelf life, decreasing food waste, and enhancing resource efficiency along the seafood supply chain, vacuum packaging promotes sustainability. Due vacuum packaging slows down oxidative degradation and microbiological spoiling, fewer fish are thrown out because of quality loss. Since lacking cold-chain infrastructure frequently results in large post-harvest losses, this is particularly crucial in underdeveloped nations. Less waste means more harvestable fish resources are used, wild stocks are less stressed, and fishermen and processors make more money. Most vacuum packaging films are petroleum-based polymers, which raise concerns related to plastic waste and environmental persistence. Current research is therefore focused on developing recyclable, lightweight and environmentally friendly packaging materials while maintaining barrier performance.

Table 1 Challenges and Limitations of Vacuum Packaging in Fish Products

Aspect	Limitation	Implication
Microbial Safety	Growth of anaerobic bacteria	Reduced oxygen may favor <i>Clostridium botulinum</i> type E if temperature control is inadequate.

Temperature Control	Strict cold-chain requirement	Temperature abuse increases safety risks and reduces effectiveness.
Economic Feasibility	High initial cost	Equipment and packaging materials may limit adoption by small-scale processors.
Biochemical Stability	Limited control of autolysis	Does not prevent enzymatic degradation and texture softening.

Future Trends and Innovations

- **Integration with Cold-Chain and Smart Technologies:** Future developments in vacuum packaging are expected to focus on integration with improved cold-chain logistics and real-time monitoring systems. Temperature indicators and freshness sensors can enhance quality control and safety assurance during storage and distribution.
- **Sustainable Packaging Materials:** The development of recyclable and biodegradable packaging films compatible with vacuum packaging is a key research priority. Such innovations aim to reduce environmental impact while maintaining the protective benefits of vacuum packaging.
- **Combination Preservation Strategies:** Vacuum packaging is increasingly being combined with other preservation techniques such as refrigeration, mild thermal treatments and natural preservatives to achieve synergistic effects in extending shelf life and ensuring safety. These hurdle-based approaches are expected to dominate future seafood preservation strategies.
- **Application in Small-Scale and Inland Fisheries:** Vacuum packaging holds significant potential for small-scale fishers and inland fisheries by enabling value addition, improving market access and reducing post-harvest losses. Low-cost vacuum packaging solutions and training programs can facilitate broader adoption in developing regions.

Conclusion

Vacuum packaging is an effective method for preserving fish and fishery products by reducing oxygen, slowing microbial growth and minimizing spoilage. When used with proper refrigeration, it significantly extends shelf life, improves quality retention and reduces post-harvest losses. Although challenges such as cold-chain dependence, anaerobic microbial risks

and packaging sustainability remain, continued innovations in materials and monitoring technologies are expected to enhance its application. Overall, vacuum packaging offers a practical solution for improving seafood quality, safety and sustainability.

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