



Smart Non-Thermal Fish Processing: Integration of Pulsed Electric Field, Cold Plasma and Artificial Intelligence for Sustainable Seafood Preservation

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ABSTRACT

Fish is a highly nutritious food and an important source of high-quality protein, omega-3 fatty acids, vitamins, and minerals. However, its high moisture content, water activity, endogenous enzymes, and unsaturated lipids make it highly susceptible to microbial spoilage, enzymatic deterioration, and lipid oxidation. Conventional preservation methods such as freezing, salting, smoking, drying, and thermal processing can extend shelf life but may affect texture, color, flavor, nutritional quality, and energy consumption. Emerging non-thermal technologies such as pulsed electric field (PEF), cold atmospheric plasma (CAP), and high-pressure processing (HPP) offer promising alternatives for seafood preservation. This article proposes an innovative concept of artificial-intelligence-integrated multi-hurdle non-thermal fish processing, combining PEF, cold plasma, HPP, smart sensors, artificial intelligence (AI), intelligent packaging, and cold-chain monitoring. PEF can support microbial control, salting, drying, and extraction, while AI can optimize processing conditions according to fish quality. The proposed system could improve safety, quality, shelf life, resource utilization, and sustainability in the seafood industry.

KEYWORDS

Fish processing, pulsed electric field, cold plasma, artificial intelligence, non-thermal processing, high-pressure processing, smart seafood

INTRODUCTION

Fish is highly perishable because its high moisture content, nutrients, endogenous enzymes, and unsaturated fatty acids provide favorable conditions for microbial growth, enzymatic reactions, and lipid oxidation. These processes rapidly reduce freshness, sensory quality, nutritional value, and economic value (Kumar et al., 2026; Peng et al., 2025). Traditional preservation methods include icing, refrigeration, freezing, salting, smoking, drying, fermentation, and canning. Although effective, some methods can cause undesirable changes in texture, color, flavor, nutrients, and energy efficiency. Increasing consumer demand for fresh-like, minimally processed, safe, and sustainable seafood has encouraged research into non-thermal processing technologies (Rathod et al., 2022). PEF, CAP, and HPP can provide microbial control with reduced thermal exposure. Among these technologies, PEF is particularly promising because electrical pulses can cause electroporation of biological membranes, influencing microbial inactivation and mass transfer (Kumar et al., 2026). The integration of such technologies with AI and real-time sensors could transform conventional fish processing into precision processing, in which treatment conditions are selected according to the characteristics of each fish batch (Peng et al., 2025).

PULSED ELECTRIC FIELD TECHNOLOGY

PEF involves exposing fish or other biological materials to short-duration, high-voltage electrical pulses. Electroporation can increase membrane permeability and contribute to microbial inactivation and mass transfer (Kumar et al., 2026).

Microbial Control

Microbial contamination is a major cause of fish spoilage. PEF can contribute to microbial reduction without intensive heating. Its effectiveness depends on electric-field strength, pulse duration, number of pulses, temperature, food composition, and microorganism characteristics (Kumar et al., 2026). Therefore, PEF is most appropriately used as one hurdle in a multi-hurdle preservation system rather than as a universal replacement for conventional processing.

Salting, Marination and Drying

Electroporation can increase tissue permeability and facilitate the movement of salt, water, and marinade components into fish tissue. PEF may therefore improve the efficiency and uniformity of salting and marination (Kumar et al., 2026).

PEF pretreatment can also enhance mass transfer during drying, potentially reducing drying time and improving process efficiency. In addition, PEF can assist the extraction of valuable compounds from fish-processing residues, contributing to by-product utilization (Kumar et al., 2026).

COLD ATMOSPHERIC PLASMA

Cold atmospheric plasma is generated by energizing a gas and producing reactive species capable of damaging microorganisms. Because it can operate at relatively low temperatures, CAP has potential for surface decontamination of fresh and minimally processed seafood (Rathod et al., 2022; Russo et al., 2024). The major advantages of CAP include low-temperature operation, rapid treatment, and potential reduction in dependence on conventional chemical sanitizers. However, excessive plasma exposure can promote lipid oxidation. This is particularly

important in fish because polyunsaturated fatty acids are highly susceptible to oxidation (Russo et al., 2024). Therefore, the treatment should use the minimum effective intensity necessary to achieve the required microbial reduction.

HIGH-PRESSURE PROCESSING

HPP uses high hydrostatic pressure to reduce microorganisms while limiting conventional heat exposure. It has potential applications in packaged fish, shellfish, ready-to-eat seafood, and other high-value products (Rathod et al., 2022).

HPP can contribute to shelf-life extension while maintaining many fresh-like properties. However, pressure can influence texture and color, and HPP equipment requires substantial capital investment. Therefore, HPP should be used selectively as an additional hurdle in an integrated preservation system.

ARTIFICIAL INTELLIGENCE IN FISH PROCESSING

AI could become the decision-making component of future fish-processing plants. Sensors could measure temperature, pH, color, firmness, moisture, electrical conductivity, freshness indicators, and temperature history. Computer vision could identify size, shape, discoloration, bruising, and physical damage.

These data could produce a digital quality profile for each batch. AI could then recommend appropriate processing conditions within scientifically validated safety limits.

A simplified system could operate as:

Fish quality assessment → AI prediction → PEF treatment → CAP/HPP → quality verification → smart packaging

Recent research has identified AI integration, improved equipment, process

optimization, and cold-chain management as important future directions for electric-field technologies in fish processing (Peng et al., 2025).

SMART PACKAGING AND COLD-CHAIN MONITORING

Fish quality can continue to deteriorate after processing because of temperature fluctuations, oxygen exposure, and microbial activity. Smart packaging could monitor temperature, oxygen exposure, package integrity, and freshness-related indicators.

Connecting these data with digital traceability systems could allow processors and retailers to monitor actual storage conditions. In the future, this may support dynamic shelf-life prediction, where remaining shelf life is estimated using real-time product and temperature information rather than relying only on a fixed expiry date.

CIRCULAR FISH PROCESSING

Fish-processing plants generate heads, skins, bones, scales, frames, and viscera. These residues contain proteins, collagen, gelatin, lipids, minerals, peptides, and other valuable compounds.

PEF can improve mass transfer and support extraction of useful components from marine biomass (Kumar et al., 2026). Thus, future facilities could operate as marine biorefineries:

Fish → premium fillets → non-thermal preservation

By-products → PEF-assisted extraction → collagen, gelatin, protein products and valuable lipids

This approach can reduce waste and increase the economic value of fish resources.

INTEGRATED PROCESSING MODEL

The proposed smart fish-processing system consists of the following stages:

1. **Smart reception:** Sensors and computer vision assess incoming fish.
2. **AI classification:** Freshness, size, quality, and microbial risk are evaluated.
3. **PEF treatment:** A validated PEF condition is selected.
4. **Multi-hurdle preservation:** CAP, HPP, refrigeration, drying, or salting may be applied.
5. **AI endpoint detection:** Sensors monitor processing conditions and quality.
6. **Smart packaging:** Product and storage information are recorded.
7. **Intelligent cold chain:** Transportation and storage conditions are monitored.
8. **By-product valorization:** Processing residues are converted into value-added products.

The complete concept can be summarized as:

Sense → Predict → Process → Verify → Package → Monitor → Valorize.

ADVANTAGES AND CHALLENGES

The proposed system could provide several advantages. Non-thermal technologies can improve microbial control while reducing some quality changes associated with intensive thermal processing (Rathod et al., 2022). PEF provides multiple applications, including microbial control, salting, drying, and extraction (Kumar et al., 2026). AI could reduce unnecessary processing by selecting conditions according to product characteristics. Smart packaging and cold-chain monitoring could further reduce food losses.

However, several challenges remain. These include high equipment costs, industrial scale-up, treatment uniformity, oxidation,

process standardization, regulatory validation, and consumer acceptance. Kumar et al. (2026) also highlighted the need for further development of PEF equipment, optimization of processing conditions, and industrial application.

CONCLUSION

The future of fish processing requires technologies that can simultaneously improve food safety, shelf life, sensory quality, nutritional retention, sustainability, and economic efficiency. PEF, cold plasma, and HPP have considerable potential for achieving these objectives (Rathod et al., 2022; Russo et al., 2024). PEF is especially promising because of its multifunctional applications in microbial control, mass transfer, salting, drying, and extraction. Kumar et al. (2026) demonstrated its potential specifically for fish preservation and highlighted opportunities for combining PEF with other emerging technologies. The integration of PEF and other non-thermal technologies with AI represents an important future direction. AI-enabled systems could assess fish quality, optimize processing conditions, monitor processing endpoints, and support shelf-life prediction. When combined with smart packaging and intelligent cold-chain management, this approach could reduce food loss and improve seafood traceability.

Although scale-up, cost, oxidation, standardization, regulation, and consumer acceptance remain important challenges, AI-integrated multi-hurdle non-thermal processing could represent a new paradigm in fish-processing technology, moving the industry toward precision, intelligent, sustainable, and circular seafood processing.

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