



The Future on Ice: Emerging Technologies in Fish Processing

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ABSTRACT

The global fish processing industry is undergoing a significant transformation driven by the need for improved product quality, extended shelf life, enhanced safety, and greater sustainability. This paper reviews emerging technologies reshaping the sector, including advanced freezing methods such as ultrasound-assisted and high-pressure freezing, which minimize ice crystal damage and preserve textural and nutritional integrity. Non-thermal processing techniques, including high-pressure processing, pulsed electric fields, and cold plasma, are examined for their ability to inactivate pathogens and extend shelf life while retaining sensory qualities. The integration of automation, robotics, and machine vision in filleting, sorting, and quality inspection is discussed as a means of increasing processing efficiency and reducing labor dependency. Additionally, the paper explores the role of smart packaging, biosensors, and blockchain-based traceability systems in ensuring food safety and supply chain transparency. Environmental considerations, such as waste valorization and energy-efficient cold chain management, are also addressed as critical components of sustainable fish processing. By synthesizing recent advances across these domains, this paper highlights the trajectory of innovation poised to redefine fish processing practices, offering insights for researchers, industry stakeholders, and policymakers seeking to balance technological progress with sustainability and food security goals.

KEYWORDS

Smart packaging; food safety; cold chain management; automation and robotics

Introduction

Seafood processing is among the oldest sectors of the food industry, but it is currently experiencing rapid technological transformation. Global aquatic animal production is continuing to expand, with the Food and Agriculture Organization of the United Nations forecasting further increases in production, consumption, and international trade over the coming decade (FAO, 2026). Meanwhile, seafood processors are facing challenges such as increasing labour expenses, more stringent food-safety and traceability requirements, and growing consumer demand for detailed information about the origin and handling of seafood products. These factors are accelerating the adoption of automation, artificial intelligence, digital traceability systems, and energy-efficient cold-chain technologies across the industry.

This review examines the key technological developments that are transforming modern fish and seafood processing. Major areas include robotic and automated processing systems, artificial intelligence-based quality assessment and grading, block chain-enabled traceability, smart cold-chain and packaging sensors, recirculating aquaculture systems (RAS) that support a reliable supply of seafood for processing, and sustainability-focused innovations in packaging and by-product utilization. The review integrates recent industry reports, FAO information, and peer-reviewed research on emerging sensor, processing, and packaging technologies.

Automation and Robotic Processing Lines

Automating fish filleting, skinning, deboning, and sorting has traditionally been difficult because fish differ considerably in size, shape, weight, and body structure compared with more uniform animal products. Recent technological developments, however, are making these operations increasingly suitable for automation. Modern processing facilities are incorporating machine-vision technologies with robotic systems

that can identify the individual shape and dimensions of fish and adjust cutting operations accordingly. These systems can improve processing speed, increase product recovery, and reduce material losses while also decreasing the physical strain associated with repetitive manual processing activities (Sasidharan et al, 2026).

The adoption of automated equipment is also being supported by the need for improved food safety, process consistency, and operational efficiency. Advanced processing machinery increasingly incorporates sensors and automated control systems that can support compliance with food-safety measures like Hazard Analysis and Critical Control Points (HACCP), as well as the quality standards and regulations proposed by the USFDA in other countries. In addition, automated systems provide more energy efficiency and improved monitoring of processing operations (Insights, F. B. 2022). Automation has consequently become an important component of large-scale seafood processing. Industrial facilities are increasingly using technologies such as automated filleting and portioning equipment, machine-based grading systems, spiral freezers, and computerized refrigeration-monitoring systems. The continued expansion of these technologies reflects the industry's demand for higher productivity, consistent product quality, reduced labor dependence, and improved resource efficiency. Market projections indicate that the seafood-processing equipment sector, including robotic filleting, portioning, sorting, and grading technologies, is expected to maintain steady growth during the coming decade (Sasidharan et al, 2026).

AI-Driven Quality Control and Freshness Sensing

Machine vision and artificial intelligence are becoming increasingly potent components to measure the quality and safety of seafood. Camera-based systems combined with machine-learning and deep-learning algorithms can assess characteristics such as fish size, shape, colour,

visible defects, and freshness rapidly and without damaging the product. Compared with conventional manual inspection, these technologies can provide more objective, consistent, and repeatable quality assessments and are increasingly being investigated for applications in automated seafood processing and grading (Zheng et al., 2026; Tariq et al., 2025).

Alongside computer-vision technologies, considerable research is being directed toward intelligent packaging systems that can monitor seafood quality during storage and distribution. These systems incorporate sensors and indicators capable of detecting changes in temperature, pH, gases, and other spoilage-related parameters. Radio-frequency identification (RFID), time-temperature indicators, pH-sensitive films, and gas sensors are among the technologies being explored for real-time monitoring of seafood freshness and storage conditions (Abedi-Firoozjah et al., 2023; Nami et al., 2024).

Colorimetric indicators are particularly promising because they can provide a simple visual indication of deterioration through changes in colour. Natural pigments and pH-sensitive materials can respond to volatile compounds and chemical changes associated with microbial spoilage. In seafood packaging, sensors designed to detect compounds such as ammonia (NH_3), hydrogen sulfide (H_2S), and total volatile basic nitrogen (TVB-N) have received considerable attention because these substances are important indicators of protein degradation and loss of freshness (Nami et al., 2024; Panwar et al., 2024). Recent developments in intelligent packaging are also combining sensor technologies with digital image analysis and mathematical or machine-learning models, creating opportunities for more quantitative and real-time assessment of seafood quality (Ameri et al., 2024).

Digital Traceability: Blockchain and Supply Chain Tracking

“Ocean-to-plate” traceability is increasingly becoming an important requirement

in international seafood supply chains, particularly as regulators, retailers, and consumers demand greater transparency regarding the origin, handling, and sustainability of seafood products. Digital technologies such as blockchain, Internet of Things (IoT) devices, and electronic tracking systems can connect information across different stages of the supply chain, allowing details such as catch location, fishing vessel, processing records, and cold-chain conditions to be recorded and accessed more efficiently. These technologies can improve transparency, support seafood safety and authenticity, strengthen efforts to address illegal, unreported, and unregulated (IUU) fishing, and increase consumer confidence in sustainably sourced products (Zhang et al., 2021; Shamsuzzoha et al., 2024). Recent research also highlights that digital traceability can improve market access and supply-chain efficiency, although high implementation costs, limited digital infrastructure, interoperability problems, and unequal access to technology remain important challenges, particularly for small-scale producers (FAO, 2007; Xue-Lønmo et al., 2026).

Smart Cold Chains and IoT Monitoring

Refrigeration, chilling, and freezing are among the most energy-demanding operations in seafood processing, making efficient cold-chain management essential for maintaining product quality, safety, and shelf life. Increasingly, Internet of Things (IoT)-based sensors, RFID devices, wireless communication systems, and real-time data platforms are being used to continuously monitor temperature, humidity, location, and other environmental conditions throughout storage and transportation, replacing conventional manual and periodic monitoring. These technologies can provide early warnings of temperature deviations, support freshness and shelf-life assessment, improve traceability, and reduce spoilage and distribution losses. Recent developments are also integrating IoT monitoring with artificial intelligence, blockchain, and other digital technologies to enable more predictive and

transparent cold-chain management across seafood supply networks (Harriz et al., 2025; Subash et al., 2024).

Recirculating Aquaculture Systems (RAS) Upstream of Processing

Recirculating aquaculture systems (RAS) are increasingly being adopted as controlled, land-based production systems capable of supplying a consistent volume of fish to seafood processing industries while using substantially less water than conventional aquaculture. Recent technological developments have focused on improving system efficiency through optimized filtration, system integration, energy management, real-time water-quality sensors, and artificial-intelligence-based monitoring. These advances are particularly relevant to the production of high-value species such as Atlantic salmon, for which land-based RAS can provide greater environmental control and biosecurity, although energy consumption remains an important challenge to their sustainability. The integration of sensors and AI-based data analysis can support continuous monitoring of parameters such as temperature, dissolved oxygen, pH, and ammonia, enabling earlier detection of abnormal conditions and more efficient system management (Badiola et al., 2018; Brown et al., 2025).

Sustainable Packaging and Byproduct Valorization

Sustainability considerations are increasingly influencing packaging, energy use, and waste-management practices within the seafood-processing industry. Processing facilities are adopting recyclable and bio-based packaging materials, water-reuse systems, energy-efficient refrigeration, and improved freezing technologies to reduce resource consumption and minimize environmental impacts. In particular, efficient refrigeration and freezing systems can help reduce energy demand while maintaining stable storage temperatures, thereby limiting quality deterioration and food losses. Research on seafood-processing sustainability also emphasizes

the importance of improving resource efficiency and recovering value from processing residues rather than treating fish by-products as waste (Hall et al., 2013).

At the same time, advances in intelligent packaging are creating new opportunities for reducing seafood waste throughout the supply chain. Smart packaging can incorporate freshness indicators, time-temperature indicators, gas-sensitive materials, and digital sensing technologies that provide information about changes in product quality during storage and transportation. These systems can help processors, distributors, retailers, and consumers make better decisions about product handling and inventory management, potentially reducing unnecessary disposal of seafood while maintaining food safety and quality (Ghaani et al., 2016; Yildirim et al., 2018).

Challenges and Adoption Barriers

The adoption of automation, artificial intelligence, robotics, and sensor-based technologies in seafood processing remains uneven because implementation requires substantial capital investment, technical infrastructure, and trained personnel. These challenges are particularly important for small and medium-sized processors, which may have limited financial resources and difficulty integrating advanced equipment into existing processing systems. In addition, the biological variability of fish, differences in species and body morphology, and the need for frequent system calibration can reduce the flexibility and reliability of automated technologies. Consequently, the transition toward digital seafood processing requires not only investment in equipment but also workforce training, technical support, and appropriate digital infrastructure (Yadav et al., 2026; Subash et al., 2024).

Smart packaging and AI-based freshness-monitoring systems also face limitations when moving from laboratory research to commercial

applications. Variations in temperature, humidity, lighting conditions, packaging materials, fish species, and product characteristics can influence sensor performance and the accuracy of AI-based models. Recent research emphasizes the need for further validation under actual transportation, storage, and retail conditions before these technologies can be widely implemented. The cost of sensors and digital monitoring systems may also restrict their use in lower-value seafood products, making adoption more economically attractive for premium, highly perishable, or export-oriented products (Ramlah et al., 2026; Nami et al., 2024).

Broader economic and supply-chain uncertainties can further influence investment decisions within the seafood sector. Changes in international trade, transportation costs, energy prices, and market conditions can affect the economic feasibility of adopting advanced processing and digital technologies. In response, seafood businesses are increasingly emphasizing operational efficiency, supply-chain resilience, automation, and better integration of production, processing, storage, and distribution activities. However, ensuring that technological progress benefits smaller processors and producers remains an important consideration for achieving an inclusive and sustainable digital transformation of the seafood industry (Subash et al., 2024; Yadav et al., 2026).

Conclusion

The technologies discussed—including automation, computer vision, blockchain, and connected sensor systems—are not exclusive to the seafood industry, as they are already being applied across various food-processing sectors. However, their rapid integration within seafood processing represents an important technological shift for an industry that has traditionally adopted advanced technologies more slowly than many other food sectors. The increasing combination of automated processing, digital traceability, intelligent monitoring, and energy-efficient cold-

chain systems is expected to improve productivity, product quality, food safety, resource efficiency, and supply-chain transparency. Seafood processors that adopt flexible and scalable technologies are therefore likely to be better prepared to respond to growing global seafood demand, stricter regulatory requirements, sustainability expectations, and increasing consumer interest in knowing the origin and production history of seafood products.

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