

Revolutionizing the Fish Packaging Industry: The Role of Sensors, IoT, and Artificial Intelligence

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Abstract

Efficient food packaging is an essential component of food processing and packaging industries as they extend shelf life, reduce food waste, improve traceability, food safety and enhance supply chain efficiency. Consequently, advancements in food packaging technology are thought to address the increasing worldwide demand for food quality and safety. Artificial Intelligence (AI) is fundamentally reshaping the food packaging industry by enhancing product quality, efficiency, and design. Furthermore, AI plays a crucial role in quality control by rapidly analyzing images to detect material defects. The combination of biosensors and the Internet of Things (IoT) is rapidly advancing food safety and traceability by moving beyond traditional, limited inspection methods. While sensors and machine learning algorithms are used during processing for compliance and monitoring, the real innovation lies in packaging. biosensors are directly integrated to monitor and identify early signs of spoilage or freshness. The IoT then acts as the crucial link, transmitting this real-time data across the entire supply chain. This constant flow of information empowers stakeholders to make proactive, informed decisions about food storage and transportation, dramatically enhancing food quality, security, and safety compared to older techniques focused only on weight or colour.

Key words: traceability, compliance, monitoring, safety, advancements, design

Introduction

Seafood is essential element of the global food supply, playing a crucial role in both nutrition and economic stability around the world due to its low-fat content and high protein levels, along with a range of micronutrients including vitamins and minerals. Over 3 billion people depend on fish as a major source of animal protein (Fulton et al., 2018). Furthermore, seafood is the primary dietary source of including eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which provide numerous health benefits, such as a lower risk of cardiovascular disease (Carlucci, 2015; Petricorena, 2015). Nonetheless, the inherent perishability of these products poses significant challenges throughout the supply chain,

especially in terms of packaging (Gokoglu, 2020) (Tsironi & Taoukis, 2018). Problems such as quick spoilage, microbial contamination, and weaknesses in maintaining the cold chain often jeopardize the quality and safety of these products (Karanth et al., 2023). To address these issues, it is necessary to incorporate advanced technological solutions to maintain freshness and ensure the integrity of the products from harvest to consumer (Hassoun & Karoui, 2017).

Advanced technologies are essential to maintain the freshness and quality of fish products due to their high perishability from moisture, unsaturated lipids, and microbial activity. In recent years, numerous advanced technologies have emerged, such as irradiation, microwave processing, ultrasound, high-pressure processing, cold plasma, radiofrequency, pulsed electric field, pulsed light technology, and innovative packaging solutions (like modified atmosphere, active, and intelligent packaging) driven by the advancements of the developing industrial revolutions and have the potential to overcome the aforementioned challenges and enhance the shelf life of fish and other sea food during processing and/or preservation (Arshad et al., 2021; Hassoun et al., 2020b; Nilsen-Nygaard et al., 2021; Rathod et al., 2021; Wu et al., 2021).

Traditionally, a variety of preservation methods like fermentation, smoking, curing, drying and conventional storage methods such as refrigeration and freezing) have been commonly used for fish and other seafood (Hassoun et al., 2020a; Tavares et al., 2021), yet these methods come with their own set of drawbacks. Traditional methods of fish packaging often fail to sufficiently protect the fragile nature of seafood. Due to their naturally short shelf life, fish products are prone to quick spoilage (Tsironi & Taoukis, 2018) (Gokoglu, 2019). Variations in temperature during storage and transportation speed up enzymatic and microbial processes, resulting in spoilage and decreased quality (Karanth et al., 2023). The growth of microbes is a constant issue, significantly affecting both safety and shelf life (Kim et al., 2017) (Karanth et al., 2023). Additionally, conventional packaging systems usually do not offer real-time monitoring, which hinders immediate corrective actions when conditions stray from ideal settings (Wu et al., 2021). This lack of active monitoring leads to considerable post-harvest losses and erodes consumer confidence.

AI in Fish packaging

Artificial intelligence (AI) is increasingly applied in fish packaging systems to enhance efficiency, freshness monitoring, and safety. Machine Learning (ML) is a branch of artificial intelligence that allows systems to automatically learn patterns from data and make predictions or decisions without the need for explicit programming. Deep Learning (DL), a subset of ML, utilizes multilayered neural networks to analyze complex patterns and high-dimensional data, enabling more advanced and accurate data interpretation (Agrawal et al., 2025). Deep learning

combined with machine vision and robotic arms enables automated sorting and packaging of seafood. For instance, Zhang et al. (2023) identified that automation in oysters, improving speed and reducing contamination risks with high grasping success rates. AI-driven systems, especially those utilizing machine vision (MV) and deep learning, provide enhanced capabilities for the inspection of fish products and their packaging. These systems employ cameras and advanced algorithms to detect defects, imperfections, and surface-level quality issues that human inspection might overlook or find inconsistent (Ma et al., 2016) (Chen & Yu, 2021). Computer vision systems are adept at classifying food products into specific grades, detecting defects, and assessing properties such as colour, shape, and size (Fracarolli et al., 2020) (Rojas Santelices et al., 2025). This non-destructive assessment method enhances food safety by ensuring only high-quality items are packaged.

Machine learning algorithms, a subset of AI, predict shelf life by analyzing various environmental and product-specific data points, facilitating better inventory management (Gbashi & Njobeh, 2024). Object detection algorithms like YOLOv7 can identify packaging flaws such as scratches, holes, and deformations in real-time, thereby preventing compromised products from entering the supply chain (Ahmed et al., 2024). Furthermore, AI systems can analyze large datasets from production, inventory, and logistics to forecast demand and optimize stock levels, reducing overproduction and waste (Adeleke and Samuel, 2024).

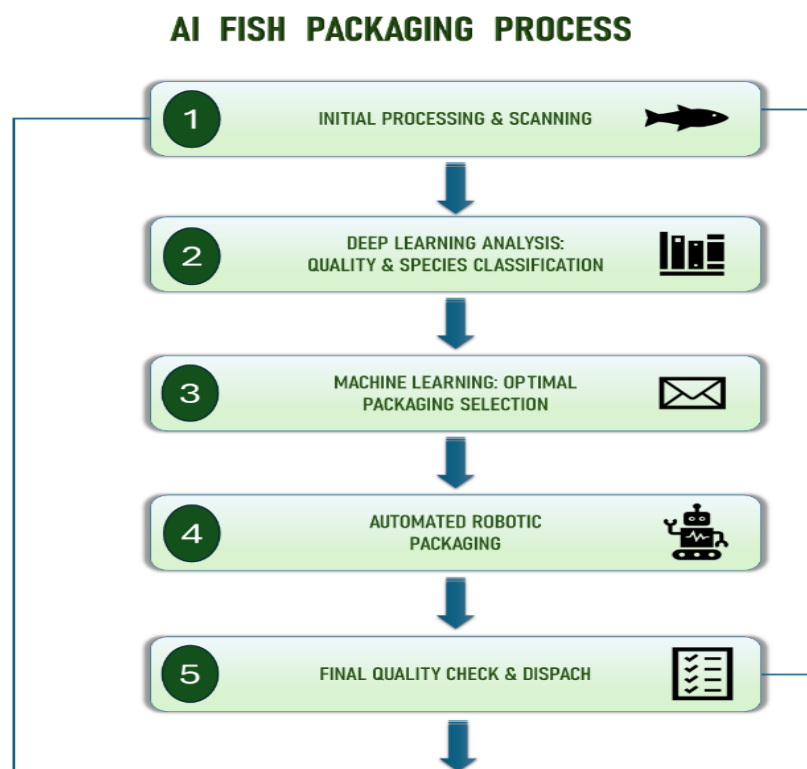


Fig 1.1 AI in Fish packaging

Beyond automation, AI enables the development of "smart" or intelligent packaging systems. Real-time data from these intelligent packages provides actionable insights into product integrity, particularly for perishable goods like fish (Madhu, 2025). For example, Time Temperature Indicators (TTIs) combined with predictive kinetic models can continuously monitor temperature history, improve the distribution of chilled products and reduce the likelihood of consumption past shelf life (Giannakourou et al., 2001).

Sensors in Fish packaging

Sensors used in the fish packaging industry primarily focus on monitoring freshness and spoilage by detecting chemical changes related to microbial activity. Common sensors include pH-sensitive dyes embedded in polymer matrices that change colour in response to volatile basic nitrogen compounds (TVB-N), which are indicators of fish spoilage provide visible colorimetric changes that correlate with freshness levels (Pacquit et al., 2006). pH-sensitive indicators are integral components of intelligent packaging for monitoring fish freshness, responding to changes in pH that occur during spoilage (Liu et al., 2022) (Ahmed et al., 2018). These indicators are typically incorporated into labels or films that visibly change colour as the pH shifts due to the accumulation of alkaline volatile compounds, such as ammonia and other biogenic amines, released by microbial activity (Wu et al., 2021).

TTI- device like "Freshtag" can be affixed to packaging to monitor whether fish has been kept within optimal low-temperature ranges during transportation and storage. Any deviation from the recommended temperature profile accelerates the indicator's progression, signalling potential spoilage or reduced shelf-life, even if the current temperature is within an acceptable range (Kuswandi et al., 2022). This provides a straightforward visual cue that helps retailers and consumers make informed decisions about product safety and quality (Ahmed et al., 2018). Electronic Noses (E-Noses) and Electronic Tongues (E-Tongues) are advanced sensory systems designed to objectively mimic human olfaction and gustation, respectively, for comprehensive food quality assessment (Calvini & Pigani, 2022) (Ebenezer et al., 2025). Biosensors integrate biological components, such as enzymes, antibodies, or aptamers, with a physicochemical transducer to detect specific chemical or biological markers associated with fish spoilage (Givanoudi et al., 2023). These devices offer high sensitivity and selectivity for rapid detection of spoilage indicators, including volatile organic gases, microorganisms, and biogenic amines (Wang et al., 2022). Biosensors integrate biological components, such as enzymes, antibodies, or aptamers, with a physicochemical transducer to detect specific chemical or biological markers associated with fish spoilage (Givanoudi et al., 2023). These devices offer high sensitivity and selectivity for rapid detection of spoilage indicators,

including volatile organic gases, microorganisms, and biogenic amines (Wang et al., 2022). Nanomaterials are frequently incorporated into biosensor design to enhance sensitivity and selectivity, enabling the detection of adulterants and contaminants with improved limits of detection (Kaur et al., 2024). Despite their precision, challenges remain in integrating biosensors into cost-effective and easy-to-use on-site applications within the food industry (Adley, 2014).

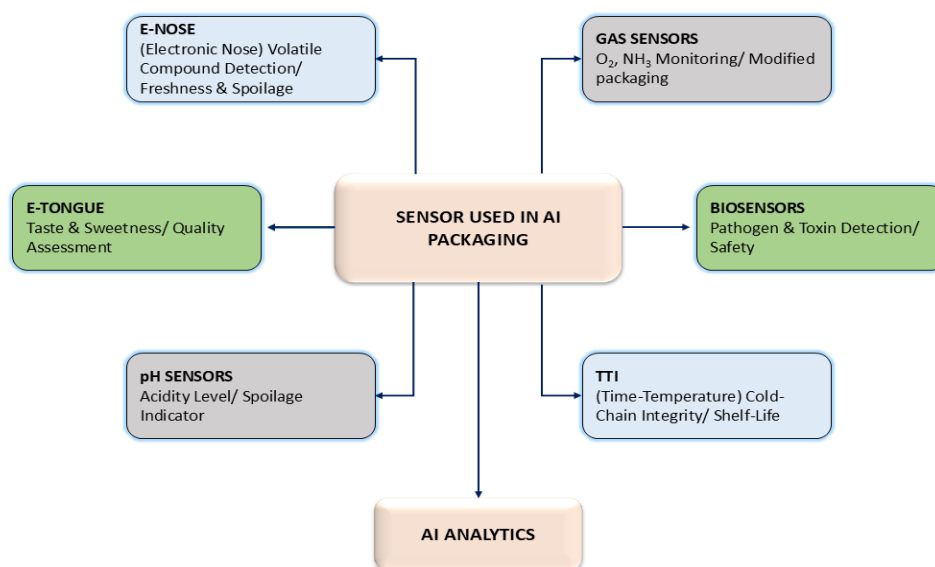


Fig 1.2 Sensors in fish packaging

Smart labels and Radio-Frequency Identification (RFID) systems represent a significant advancement in fish packaging, providing real-time tracking, enhanced traceability, and direct communication of freshness data (Wu et al., 2021) (Ahmed et al., 2018). RFID tags, particularly near-field and ultrahigh frequency (UHF) wireless passive sensors, can track critical parameters like bacterial count, volatile gas concentration, humidity, and pH (Raju et al., 2020).

IoT in Fish packaging

IoT (Internet of things) an efficient real-time monitoring system, plays an important role in ensuring cold-chain integrity in fish packaging. Smart packaging systems equipped with IoT sensors can continuously track environmental factors such as gas composition, temperature, and microbial activity, triggering controlled release of preservatives to extend shelf life by up to 14 days (Douaki et al., 2025). IoT integration with blockchain technology enhances traceability and transparency, helping to prevent illegal activities and ensuring authenticity from harvesting to delivery (Ismail et al., 2023). Additionally, IoT-enabled biosensors transmit data on spoilage indicators to cloud platforms, allowing stakeholders to

make proactive decisions and improve food safety management (Sobhan et al., 2025). Modified atmosphere packaging combined with IoT allows remote monitoring and precise control of gas mixtures that preserve fish freshness, reducing waste and operational costs (Lin et al., 2025). Overall, IoT facilitates intelligent, connected packaging solutions that improve sustainability, reduce food loss, and optimize supply chain efficiency in the fish industry (Subash et al., 2024) (Manaswini et al., 2025).

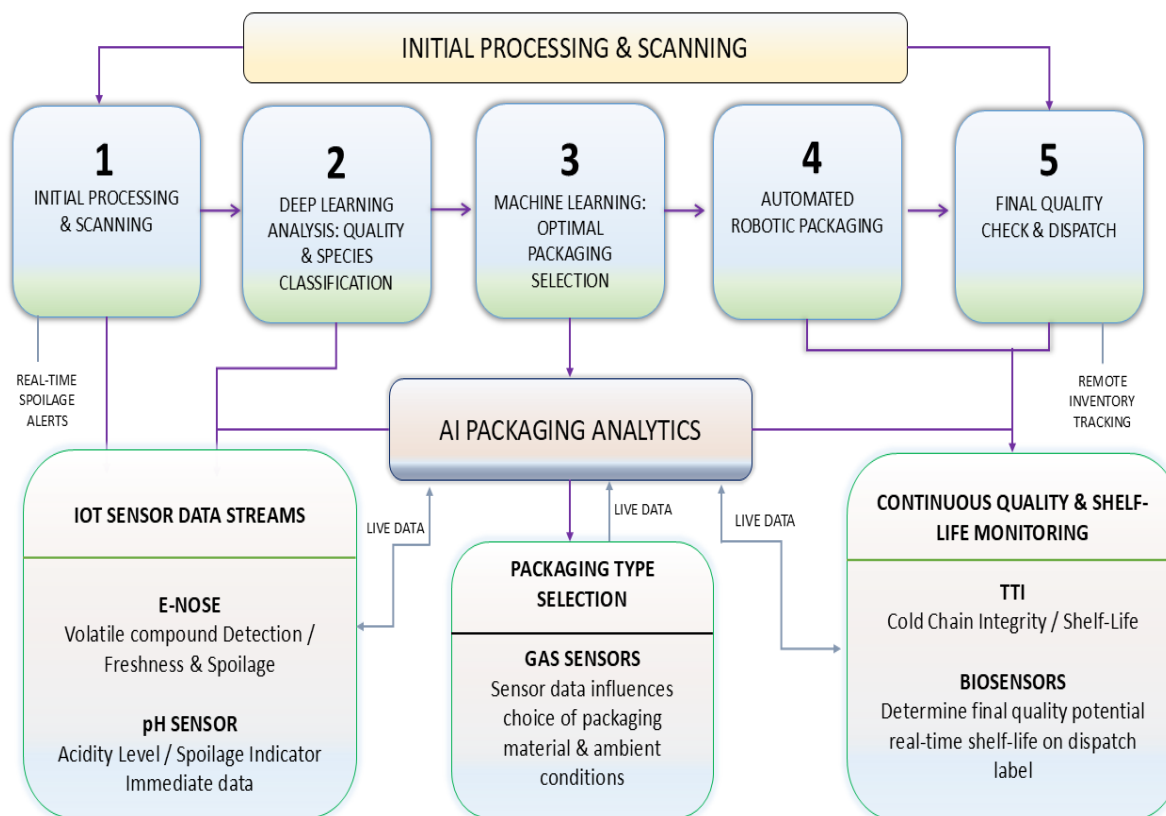


Fig 1.3 Integration of AI, Sensors and IoT in fish packaging industry

Conclusion

The integration of AI, sensors, and IoT is transforming fish packaging by facilitating intelligent monitoring, better quality control, and improved traceability throughout the supply chain. These technologies ensure optimal storage conditions, allow for early detection of spoilage, and help minimize post-harvest losses. Their adoption can significantly extend shelf life, ensure food safety, and improve efficiency in the seafood industry. Overall, smart packaging driven by AI and IoT represents a promising step toward a more reliable, sustainable, and technology-driven fish packaging solution.

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