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Recent Advances in Fish Freshness Assessment Using Smart Sensors and AI

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The freshness of fish is a crucial factor influencing the safety, nutritional value, and market worth of seafood. Traditional methods for assessing freshness, such as sensory evaluations, chemical tests (like TVB-N, TMA, and pH), and microbiological plate counts, tend to be time-consuming, invasive, and not suitable for real-time analysis. In the last ten years, the emergence of smart sensor technologies including biosensors, electronic noses (e-noses), colorimetric indicators, and spectroscopic systems has significantly changed the approach to freshness evaluation. By combining these technologies with artificial intelligence (AI) and machine learning (ML) algorithms, it is now feasible to conduct automated, non-invasive, and highly precise quality assessments. This article explores the latest advancements in smart sensor-based freshness evaluation, emphasizes the significance of AI-driven analytical frameworks, investigates practical uses in seafood processing and cold chain management, and discusses the challenges that need to be addressed for broader implementation.

Keywords: Fish freshness, smart sensors, biosensors, electronic nose, artificial intelligence, seafood quality

Introduction

Fish is one of the most perishable food commodities due to its high moisture content, neutral pH, and rich enzymatic activity, making it susceptible to microbial spoilage and lipid oxidation immediately after death. Spoilage results in the formation of biogenic amines and volatile compounds, making fish organoleptically unacceptable and potentially dangerous, with histamine accumulation leading to scombroid poisoning posing a significant public health concern. Economic losses from fish spoilage reach billions of dollars annually across the supply chain. There is therefore an urgent demand for rapid, reliable, and preferably non-destructive methods to assess freshness from harvest to point of sale.

Traditional Methods and Their Limitations

Traditional methods for assessing fish freshness include sensory evaluations (such as colour, odour, texture, and appearance), chemical analyses measuring TVB-N, TMA, and pH, and microbiological techniques like total viable counts. Although these methods are considered the regulatory gold standard, they have significant drawbacks: they are time-consuming (with microbiological tests taking 24–72 hours), inherently destructive, subject to subjective bias in sensory evaluations, and fundamentally unsuitable for continuous, real-time, or inline monitoring along the cold chain.

Smart Sensor Technologies

1. Biosensors: Biosensors combine a biological recognition element with a transducer to generate quantifiable signals. Electrochemical biosensors detect freshness markers, including hypoxanthine (Hx), xanthine, and biogenic amines. The K-value, the ratio of Hx and inosine to total ATP-related compounds, is a key freshness index that enzyme-based amperometric biosensors can measure in under 10 min. Aptamer-based biosensors offer improved specificity for histamine and cadaverine, while optical biosensors using surface plasmon resonance (SPR) enable label-free, real-time monitoring of spoilage metabolites.

2. Electronic Nose (E-Nose): The electronic nose (E-nose) is an innovative sensor device designed to replicate the human sense of smell, offering a non-invasive method for evaluating the freshness of fish. Typically, E-noses consist of an array of gas sensors, such as metal oxide semiconductor sensors, which detect volatile organic compounds emitted during fish decomposition. A study demonstrated the effectiveness of a portable E-nose system named "Mastersense," which employs four MOS sensors to evaluate the freshness of meat and fish by analysing their odour profiles.

3. Colorimetric Sensors: Colorimetric sensors utilize pH-sensitive dyes that change colour in response to spoilage VOCs, such as TMA and ammonia. These dyes are printed on flexible substrates and incorporated into packaging to form intelligent labels that provide a visible indication of freshness in real time. Researchers have developed anthocyanin-based indicators within a chitosan matrix that exhibit consistent colour changes across specific spoilage stages. Recent advancements have integrated these arrays with smartphone cameras for digital colour readouts, allowing semi-quantitative freshness assessment without the need for specialized equipment.

4. Spectroscopy: Near-infrared (NIR) spectroscopy, hyperspectral imaging (HSI), and Raman spectroscopy provide non-invasive, detailed molecular analyses of fish tissue. HSI captures both spatial and spectral data simultaneously, identifying spoilage variations across the surface of fish fillets, a capability that point-measurement chemical methods lack. Researchers applied convolutional neural networks to HSI data of grass carp, achieving a TVB-N prediction accuracy of $R^2 = 0.96$ for the model. Portable NIR spectrometers now facilitate inline screening of TVB-N and K-values directly on processing lines.

Role of Artificial Intelligence

1. Machine Learning and Pattern Recognition: Smart sensors generate high-dimensional datasets requiring advanced analytical tools. Classical chemometrics (PCA, PLS-R, LDA) have long supported e-nose and spectroscopic analysis, but support vector machines (SVM), random forests, and deep learning architectures particularly CNNs have significantly improved classification accuracy. Transfer learning allows models trained on one species to adapt to new fish types with minimal retraining, enhancing practical generalizability across diverse seafood supply chains.

2. Shelf-Life Prediction and Automation: AI models enable continuous shelf-life prediction rather than simple categorical classification. Long short-term memory (LSTM) networks applied to time-series cold chain sensor data estimate remaining shelf-life dynamically as a function of temperature history, packaging atmosphere, and initial microbial load. IoT-connected sensor nodes stream real-time quality data to cloud AI platforms, triggering automated alerts at threshold breaches. Computer vision systems powered by deep learning grade whole fish on processing lines at production-line speeds, assessing eye clarity, gill colour, and skin integrity with superhuman consistency.

Applications

Inline NIR and e-nose systems integrated into filleting lines enable continuous non-destructive freshness screening, supporting HACCP compliance with objective, time-stamped quality records at critical control points. In cold chain management, smart packaging transmits real-time quality data to logistics platforms, enabling dynamic routing to prioritize temperature-compromised batches. Consumer-facing smart labels readable by smartphones allow freshness verification at point of purchase, while aquaculture operations deploy biosensor-equipped monitoring systems to optimize harvest timing and reduce post-harvest losses (FAO, 2022).

Advantages and Challenges

The main advantages are quick results (within seconds to minutes), no harm to items, fairness, and the ability to keep track continuously. However, there are challenges like sensors losing accuracy over time, models not being effective for different species, no consistent rules for new freshness measures, and the high cost of advanced systems being too expensive for small businesses. The key goals for the next decade are to standardize methods, develop strong AI models for various species, and make devices smaller.

Conclusion

The integration of smart sensor technologies with artificial intelligence marks a significant evolution in the evaluation of fish freshness, moving away from traditional methods that are time-consuming, damaging, and subjective, towards approaches that are quick, automated, and objective. By combining biosensors, electronic noses, colorimetric indicators, and spectroscopic platforms with machine learning and deep learning, these systems offer precise freshness assessments that can be utilized in processing facilities, cold storage, and retail settings. To fully harness the capabilities of these integrated systems, it is essential to advance sensor durability, enhance AI adaptability, and achieve international regulatory alignment for efficient global seafood supply chain management.

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