Application and Development of Intelligent Food Packaging in Food Freshness Monitoring

Zixi Yue

Tianjin Farragut School, Yantai Road No.3, Tianjin, 300000, China

lamianxidengni@qq.com

Abstract. Intelligent food packaging, also referred to as smart packaging, has emerged as a promising solution for enhancing food safety, quality assurance, and supply chain transparency. By embedding sensing, indicating, recording, and communication functionalities into packaging systems, intelligent packaging enables real-time or near-real-time monitoring of environmental and intrinsic food conditions. This review summarizes the classification of intelligent packaging technologies by functional roles, sensing targets, and integration approaches. The fundamental detection principles, including colorimetric indication, electrochemical sensing, gas/volatile compound monitoring, biorecognition, and mass-sensitive detection, are discussed in detail. This paper also reviews the enabling manufacturing technologies such as printed electronics, microfluidics, Micro-Electro-Mechanical Systems (MEMS), and Internet of Things (IoT)-enabled communication modules. Advantages, including freshness monitoring, pathogen detection, traceability, and food waste reduction, are considered alongside challenges in stability, cost, scalability, regulatory compliance, and environmental sustainability. Representative applications in seafood spoilage detection and fruit and vegetable ripening monitoring demonstrate practical implementations and current challenges. The findings suggest that multimodal integration, advanced nanomaterials, machine learning algorithms, and sustainable design will drive future development toward large-scale adoption of intelligent food packaging systems.

Keywords: Intelligent packaging solutions, Food protection and safety, Sensor technologies, Internet-of-Things applications, Micro-electromechanical systems.

1. Introduction

Ensuring the safety of food products and preserving their quality has become a central concern in modern supply chains. With global trade expanding and consumers increasingly demanding freshness, the industry faces mounting pressure to adopt advanced monitoring solutions [1]. Conventional quality assessment methods-such as laboratory chemical analyses, microbiological tests, and human sensory evaluation-although widely applied, often suffer from drawbacks including long turnaround times, limited testing capacity, and the inability to deliver continuous real-time feedback throughout distribution channels. To overcome these deficiencies, the concept of intelligent packaging has emerged. This technology embeds functional elements such as indicators, miniaturized sensors, and data-transmission components directly into the packaging itself, creating a platform that continuously communicates information on product condition [2, 3]. Unlike active packaging systems, which intervene by modifying the internal environment through actions such as absorbing oxygen or releasing antimicrobial substances, intelligent packaging is primarily focused on monitoring and signaling. Its main role is to detect relevant changes and convey this information to stakeholders, thereby improving decision-making in production, logistics, and end-use contexts [4].

The classification of intelligent packaging can be approached from multiple perspectives [5]. Functionally, it may include visual indicators, sensing modules with data storage capability, product traceability carriers, as well as IoT-enabled communication units [6]. Based on detection objectives, applications range from monitoring physical and environmental parameters, identifying chemical byproducts of degradation, to recognizing microbial or biological contamination, with multimodal systems often employed to increase accuracy and robustness [7]. From the standpoint of integration, formats vary widely-from disposable single-use labels to advanced systems that rely on microfluidic structures and MEMS-based technologies. Furthermore, the detection principles underlying these systems are diverse, encompassing approaches such as color-change indicators, electrochemical sensing, volatile compound detection, biospecific recognition assays, and mass-sensitive platforms, each tailored to address aspects of food quality evaluation [8, 9].

This review provides an in-depth synthesis of intelligent packaging technologies, focusing on their classification schemes, working principles, fabrication methods, advantages and drawbacks, as well as representative applications in monitoring seafood spoilage and fresh produce ripening. By consolidating recent progress and addressing unresolved challenges, the study outlines possible directions for advancing sustainable, efficient, and consumer-oriented intelligent packaging solutions [10].

2. Overview of Intelligent Food Packaging

Intelligent food packaging, often termed smart packaging, constitutes an emerging technological system in which sensing, indicating, recording, and communication modules are embedded directly into the package. Through this integration, packaging is transformed into an information carrier capable of real-time or near-real-time monitoring of both environmental conditions and the internal state of food. Such systems play an important role in safeguarding quality, extending and predicting shelf-life more accurately, improving supply chain visibility, and supporting consumer trust. Unlike active packaging-which modifies the food microenvironment by mechanisms such as antimicrobial release or oxygen removal-intelligent packaging emphasizes detection, signaling, and data transmission functionalities [11, 12].

2.1. Classification of Intelligent Food Packaging

The categorization of intelligent packaging can be approached from three perspectives: function, sensing targets, and system integration (Table 1). Functionally, these systems include indicators, which provide visible signals through colorimetric or fluorescent responses (e.g., pH-responsive labels, amine-reactive dyes, and time-temperature indicators, TTIs); sensors and data loggers, which continuously measure and record physicochemical variables such as temperature, oxygen, or carbon dioxide (e.g., electronic nose arrays, gas sensors); and traceability carriers, including Radio Frequency Identification (RFID), Near Field Communication (NFC), and QR codes that facilitate identification and supply chain management. A further category involves IoT-enabled communication units that transmit collected data to cloud-based platforms for algorithmic processing.

From the perspective of sensing targets, monitoring may be directed toward external conditions such as temperature, relative humidity, and gaseous composition (O_2, CO_2, ethylene, H_2S). In addition, chemical markers of deterioration-such as volatile organic compounds (VOCs), total volatile basic nitrogen (TVB-N), histamine, pyruvate, and lactate-are tracked. Biological indicators focus on microbial presence or metabolic by-products, often identified via immunological assays or nucleic acid detection. Hybrid or multimodal systems combine different sensing strategies; for example, integrating electronic-nose techniques with chromatographic, optical, or electrochemical methods can significantly enhance detection precision.

From the standpoint of system integration, intelligent packaging technologies exhibit a wide spectrum of formats. At the simplest level are inexpensive, single-use designs such as paper- or dye-based labels that provide direct visual readouts. At a more advanced stage, flexible electronic platforms created with conductive inks enable scalable electrochemical sensing. Even greater complexity is seen in microfluidic and lateral-flow devices, which incorporate antigen or nucleic acid assays in combination with enzymatic reactions. In addition, MEMS-driven systems and electronic modules have been developed, embedding processors and wireless communication functions for tasks such as temperature tracking or active RFID-based identification. An overview of these classifications, along with representative applications, is summarized in Table 1.

Table 1. The classification framework for smart food packaging is based on functionality, monitored parameters, and system integration approach

Dimension	Category	Description	Examples
Function	Indicators	Provide direct visual cues through chromatic/fluorescent changes	pH indicator strips, amine-reactive colorimetric labels, TTIs
	Sensors & Data-loggers	Real-time measurement & recording of physicochemical parameters; local/remote readout	Temperature loggers, O_2/CO_2 sensors, electronic nose arrays
	Identification & Traceability Carriers	Support product identification and supply chain tracking	RFID, NFC tags, QR codes
	Communication/IoT-enabled Nodes	Wireless transmission for cloud-based analysis	Smart labels with IoT connectivity
Sensing Target	Environmental Parameters	Detect physical condition and gases	Temperature, humidity, O_2, CO_2, ethylene, H_2S
	Chemical Markers	Monitor spoilage-related chemicals/metabolites	VOCs, TVB-N, histamine, pyruvate, lactate
	Biological/Biochemical Markers	Identify microbial contamination/metabolic activity	Pathogens, total viable counts, immunological or nucleic acid-based detection
	Hybrid/Multimodal Systems	Combine multiple sensing modalities for higher accuracy	Electronic nose + chromatographic, optical, or electrochemical methods
Integration / Implementation Mode	Disposable Paper-based/Dye Indicators	Low-cost, single-use, visually interpretable	pH strips, amine-responsive strips
	Printed Electronics/Flexible Sensors	Conductive-ink-based circuits for scalable detection	Electrochemical printed electrodes
	Microfluidic/Lateral-flow Devices	Miniaturized systems for biochemical detection	Antigen/nucleic acid test kits, enzymatic assays
	MEMS/Electronic Modules (Active Devices)	Power-supplied, with processors & communication	Temperature data loggers, active RFID tags

2.2. Fundamental Principles of Detection

Detection principles in intelligent packaging mainly encompass chemical–colorimetric reactions, physical/electrochemical sensing, molecular recognition, and bio-signal amplification techniques. Key representative approaches include:

2.2.1 Chemical/colorimetric indicators

These systems employ dyes or pH-sensitive molecules that produce visible color changes when interacting with specific analytes such as amines, acids, or oxygen. Examples include acid–base indicators responding to volatile acids and amine-reactive dyes providing distinct chromatic shifts [13].

2.2.2 Electrochemical sensors

Electrochemical methods-amperometric, potentiometric, or impedimetric-detect changes in current, potential, or impedance arising from analyte interactions or enzyme-catalyzed reactions. Applications include monitoring H_2O_2 or histamine derivatives. These sensors offer rapid responses and high sensitivity, though they may face challenges from electrode degradation and matrix effects [14].

2.2.3 Volatile compound detection

Detection of gases or volatile organic compounds employs metal oxide semiconductors, conductive polymers, or fluorescent/optical probes. Such techniques are widely used for monitoring spoilage in seafood and meat through amine and sulfide detection.

2.2.4 Biorecognition-based detection

Systems using antibodies, aptamers, or oligonucleotides selectively capture target microorganisms or toxins. Signal transduction is achieved via enzymatic reactions, nanoparticles, or electrochemical amplification. Emerging CRISPR-based platforms provide rapid, highly sensitive detection.

2.2.5 Mass-sensitive sensors

Techniques like quartz crystal microbalance (QCM) or surface acoustic wave (SAW) sensors detect surface mass changes or molecular adhesion, suitable for both volatile compounds and biomolecular interactions. These are typically applied in research or high-end monitoring contexts.

2.2.6 TTIs and thermosensitive materials

TTIs accumulate thermal exposure through irreversible physical or chemical transformations. Coupled with kinetic models of diffusion, polymerization, or enzymatic activity, they can estimate remaining shelf life [15]. The basic principle roadmap of intelligent packaging detection is shown in Figure 1 [16].

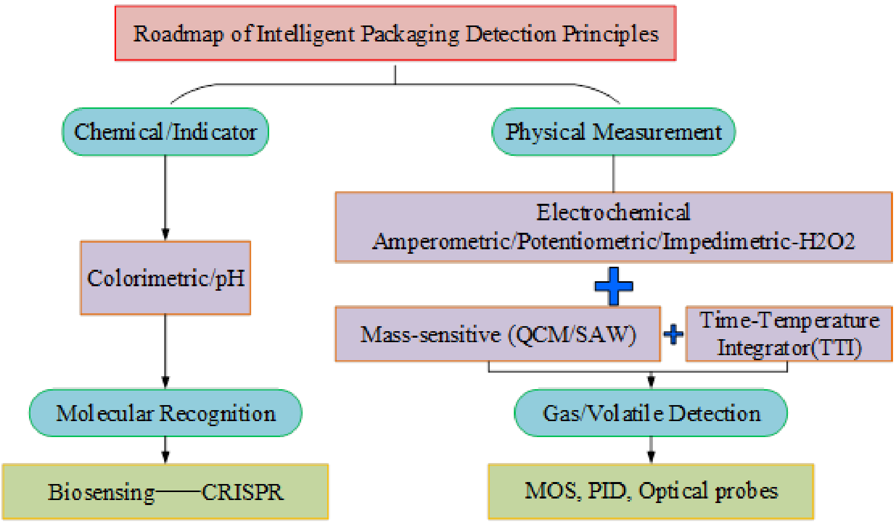

Figure 1. Roadmap of the basic principles of intelligent packaging inspection

2.3. Enabling and Manufacturing Technologies

Realizing intelligent food packaging involves diverse fabrication methods and sensor integrations. Flexible printed electronics can be produced using inkjet or screen printing of conductive nanomaterials (e.g., carbon or silver) with thin-film encapsulation for cost-effective, pliable tags. Chromatographic and colorimetric test strips allow rapid, low-cost monitoring of pH, amines, or peroxide levels. Microfluidic lab-on-a-chip platforms provide compact, on-site antigen or nucleic acid detection with built-in pretreatment and amplification. Gas sensor arrays (electronic noses) utilize multichannel MOS or conductive polymer sensors combined with machine learning for odor pattern recognition. NFC, RFID, and BLE tags, enhanced with energy harvesting (thermoelectric or photovoltaic), enable passive or active data transmission. Smartphone-based optical readouts allow convenient colorimetric or reflectance measurements, which can be integrated with cloud-based analytics for traceability and decision support. Environmentally friendly materials, such as paper substrates, natural dyes (e.g., anthocyanins), and carbon-based conductive inks, improve recyclability and reduce ecological impact.

2.4. Advantages and Limitations

Intelligent packaging provides real-time or near-real-time insight into product quality, surpassing static expiration-date assessments. This capability enhances freshness evaluation, reduces premature disposal, and mitigates food waste. Early detection of pathogens and toxins safeguards public health. IoT-enabled traceability improves supply chain transparency, regulatory compliance, and consumer confidence, while smart labels can differentiate products for marketing benefits. However, limitations exist. Food matrices may interfere with sensor accuracy, biological components may degrade over time, and printed electronics may be sensitive to moisture or mechanical stress. High-sensitivity devices remain costly, and large-scale deployment faces challenges in safety, regulatory compliance, energy supply, and data privacy. Recycling of electronic components poses environmental concerns, and international standardization of thresholds and interpretability across products is lacking [17].

3. Case Studies in Food Quality Monitoring with Intelligent Packaging

This section presents representative case studies focusing on seafood (fish and shellfish) spoilage monitoring and fresh fruits and vegetables (respiration and ethylene-related indices). For each case, the technological implementation, challenges, and limitations are discussed, followed by prospective directions and recommendations.

3.1. Case 1: Seafood (Fish and Shellfish)

3.1.1 Background and conventional quality indices

Spoilage in fish and shellfish often involves accumulation of biogenic amines (e.g., trimethylamine, total volatile basic nitrogen, histamine), which are linked to safety risks. Traditional methods-sensory, chemical, microbiological-are accurate but labor-intensive and unsuited for real-time monitoring.

3.1.2 Intelligent packaging applications

To address the limitations of conventional seafood quality monitoring, intelligent packaging systems have been developed to provide direct, real-time spoilage information. One widely used approach involves colorimetric amine indicators, where dyes immobilized on paper or polymer films-such as acid-base reagents or aldehyde/imine-binding molecules-exhibit visible color transitions in response to elevated volatile amine levels. These changes can be further quantified through smartphone-based imaging and RGB analysis, allowing semi-quantitative monitoring accessible to consumers and supply chain operators.

In addition, electrochemical amine sensors utilize electrodes modified with molecularly imprinted polymers (MIPs) to selectively bind amines, producing measurable changes in oxidation current or impedance. This enhances both sensitivity and specificity compared to traditional chemical indicators. Advanced gas sensor arrays, often referred to as electronic noses (e-noses), combine multiple MOS or conductive polymer sensors to detect complex odor profiles. Electronic noses, when trained with odor libraries and optimized by machine learning, can reliably discriminate spoiled seafood from fresh samples. Meanwhile, biosensing platforms targeting histamine-whether enzymatic, antibody-based, or aptamer-assisted electrochemical devices-offer precise detection, helping to prevent scombroid intoxication and safeguard consumer health.

3.1.3 Technical challenges

Despite recent progress, practical barriers still restrict broader implementation. Since volatile amines or TVB-N do not show a strictly proportional relationship with microbial activity-and outcomes are further shaped by species, handling, and storage-depending on a single spoilage index cannot ensure reliable safety evaluation. Environmental conditions, including high humidity and salt concentrations common in seafood packaging, can compromise the stability of paper-based indicators and electronic devices. Calibrating sensor sensitivity is also challenging, as regulatory thresholds and sensory acceptability for TVB-N and trimethylamine vary by region and species, requiring customized calibration protocols. Temperature fluctuations further affect volatile production, necessitating integration with TTIs or temperature loggers for meaningful interpretation. Finally, consumer misreading of subtle color changes can reduce the reliability of results, highlighting the need for clear, digitized, or guided readout systems [18].

3.1.4 Future perspectives

The next generation of intelligent seafood packaging is expected to integrate multiple complementary strategies. Multimodal approaches, combining chemical amine indicators, TTIs, temperature sensors, and e-nose arrays with data fusion algorithms, can improve diagnostic accuracy and robustness. To enhance durability under humid and saline conditions, advanced substrates and coatings-such as hydrophobic/hydrophilic composite films with salt-spray resistance-are being developed. Detection accuracy can also benefit from localized machine learning models, which construct species- and supply-chain-specific databases to reduce false positives. Low-cost, cold-chain-stable aptamer-based histamine sensors are moving toward practical deployment as disposable tags. In parallel, user interfaces leveraging NFC or smartphone-based readouts can deliver unambiguous, actionable guidance (e.g., “safe,” “test before consumption,” “discard”), improving usability and consumer confidence across diverse markets.

3.2. Case 2: Fresh Fruits and Vegetables

3.2.1 Background

The quality and shelf life of fruits and vegetables are closely linked to ripening and senescence, processes primarily regulated by the plant hormone ethylene. Monitoring indicators such as carbon dioxide release, oxygen consumption, and ethylene levels offers a reliable approach to evaluating fruit and vegetable ripening stages and anticipating potential spoilage. Advanced intelligent packaging technologies facilitate continuous observation of these metrics, supporting precise control of cold-chain conditions and modified-atmosphere storage.

3.2.2 Technological implementations

Assessment of fruit quality can be achieved by simultaneously monitoring ethylene, respiration, and moisture levels. Highly sensitive electrochemical or optical fluorescence probes detect ethylene at trace concentrations, while compact CO_2 and humidity sensors provide continuous data on metabolic activity and water loss. Active packaging components-such as adjustable-permeability films or smart venting systems-modulate gas exchange to decelerate ripening. In parallel, optical or colorimetric sensors capture variations in surface metabolites and volatile aroma compounds, offering an integrated perspective on maturation. Together, these approaches enable real-time, non-invasive evaluation of freshness throughout the supply chain [19].

3.2.3 Technical Challenges and Limitations

Monitoring ethylene at very low concentrations requires highly sensitive and selective sensors that are resistant to interference from other gases and do not release substances that could affect physiology. Spatial heterogeneity of ripening within packaging units complicates accurate batch-level evaluation, as localized sensor readings may not reflect overall quality. Rapid ethylene accumulation and fluctuating metabolic activity necessitate optimized sensor response times, sampling rates, and energy-efficient operation. Integrating sensor data into closed-loop control systems-for example, linking them with gas-permeable films or storage chamber actuators-remains challenging due to system complexity and reliability concerns.

3.2.4 Future Directions

Next-generation strategies emphasize low-cost, ultra-sensitive ethylene sensors based on nanomaterials or advanced spectroscopic methods. To address spatial variability, distributed, disposable short-lifespan labels can be deployed across pallets or packaging units, with centralized data fusion providing accurate batch-level monitoring. Coupling detection with active packaging allows real-time interventions, such as controlled release of ethylene scavengers or adjustment of membrane permeability, effectively preserving freshness. Furthermore, predictive modeling using machine learning, integrating ethylene, CO_2, humidity, temperature, and postharvest history, can forecast optimal consumption windows and improve supply chain decision-making [20].

4. Conclusion

Intelligent packaging represents a major advancement in achieving safer, fresher, and more sustainable food systems. By providing real-time sensation, monitoring, and communication, it enables dynamic quality assessment, extends shelf life, reduces waste, and enhances supply chain transparency. Case studies in seafood and produce illustrate its potential to address critical preservation challenges.

However, issues such as sensor stability, manufacturing cost, scalability, regulatory compliance, and environmental impact must be addressed for widespread industrial adoption. Future development is likely to focus on multimodal sensing integration, low-cost nanomaterials, energy-harvesting technologies, and machine learning-based predictive tools, alongside the use of eco-friendly materials and circular design approaches. The convergence of materials science, biotechnology, electronics, and data analytics will facilitate the transition from prototypes to large-scale industrial applications, ultimately transforming food safety and quality management practices.

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