

Smart Packaging and Freshness Sensor Technologies for Real-Time Food Quality Monitoring: A Comprehensive Review of Innovations, Applications, and Sustainability Impacts

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Abstract

Smart packaging has emerged as a transformative approach in modern food systems, enabling real-time monitoring of food quality, safety, and freshness throughout the supply chain. Unlike conventional passive packaging, smart packaging integrates sensing, communication, and response mechanisms to detect biochemical and environmental changes in food products. Freshness sensors, biosensors, and intelligent indicators play a crucial role in extending shelf life, reducing food loss, and enhancing consumer trust. This review critically examines recent developments in smart packaging and freshness sensor technologies, focusing on sensor types, functional materials, data integration, and industrial applications. Emphasis is placed on sustainability, scalability, and the role of intelligent packaging in addressing global food safety challenges. Current limitations, regulatory concerns, and future research directions are also discussed to provide a holistic understanding of the evolving smart packaging landscape.

Keywords : Smart packaging, Freshness sensors, Real-time food quality monitoring, Intelligent food packaging, Food safety, Shelf-life prediction, Perishable food products, Sensor-based packaging

1. Introduction

The growing complexity of global food supply chains has intensified concerns related to food safety, quality degradation, and post-harvest losses. Conventional food packaging systems primarily serve as passive barriers, offering limited ability to respond to dynamic changes in food condition. In contrast, smart packaging technologies introduce active and intelligent functionalities that enable continuous monitoring of freshness, spoilage, and contamination during storage and distribution (Dodero et al., 2021; Mani et al., 2025).

Recent years have witnessed significant advancements in sensor-based packaging systems, driven by innovations in nanomaterials, biosensing platforms, and digital technologies. Smart packaging integrates freshness indicators, gas sensors, time–temperature indicators, and biosensors capable of detecting microbial growth, volatile compounds, and physicochemical changes in food matrices (Palanisamy et al., 2025; Davidescu et al., 2025).

The integration of artificial intelligence, Internet of Things (IoT), and data analytics has further expanded the capabilities of smart packaging, enabling predictive shelf-life modeling and real-time decision-making

(Sagar & Rani, 2026; Bhatlawande et al., 2023). These technologies not only enhance food safety but also contribute to sustainability by reducing unnecessary food waste and improving supply chain efficiency (Soundara Rajan & Wani, 2025).

This review synthesizes recent literature on smart packaging and freshness sensors, focusing on technological innovations, functional mechanisms, practical applications, and sustainability considerations. By consolidating current knowledge, the review aims to identify research gaps and future opportunities for scalable implementation in the food industry.

2. Overview of Smart Packaging Systems

Smart packaging refers to packaging systems that incorporate intelligent features capable of sensing, recording, and communicating information about food quality and environmental conditions. These systems are broadly classified into intelligent packaging and active packaging, with intelligent packaging emphasizing monitoring and information delivery (Dodero et al., 2021).

Intelligent packaging systems utilize indicators and sensors that respond to changes in temperature, pH, gas composition, and microbial activity. Time–temperature indicators provide visual cues regarding thermal exposure, while freshness indicators detect metabolic by-products such as ammonia or sulfur compounds generated during spoilage (Mkhari et al., 2025).

Recent technological developments have focused on improving sensor sensitivity, response time, and compatibility with different food matrices. The incorporation of nanomaterials has enhanced sensor performance by increasing surface area, reactivity, and signal stability (Bhatlawande et al., 2023). Additionally, flexible and biodegradable substrates are being explored to align smart packaging with sustainability goals (Davidescu et al., 2025).

Smart packaging systems are increasingly integrated with digital platforms, enabling data logging and remote monitoring. Such integration supports traceability, transparency, and improved quality control across the food supply chain (Sagar & Rani, 2026).

3. Freshness Sensors and Detection Mechanisms

Freshness sensors are central components of smart packaging systems, designed to detect real-time changes associated with food spoilage and degradation. These sensors operate by monitoring chemical, biological, or physical markers that indicate loss of freshness (Mani et al., 2025).

Gas sensors are among the most widely used freshness indicators, detecting volatile organic compounds produced during microbial activity. For example, sensors targeting ammonia, hydrogen sulfide, and carbon dioxide are commonly applied in meat, seafood, and dairy packaging (Dodero et al., 2021).

Biosensors represent another significant advancement, employing enzymes, antibodies, or microbial receptors to detect pathogens and spoilage-related metabolites. These biosensors offer high specificity and sensitivity, making them suitable for real-time food safety monitoring (Palanisamy et al., 2025).

Colorimetric and fluorescent sensors provide visual indicators that are easily interpreted by consumers and retailers. These sensors change color in response to pH shifts or gas accumulation, offering a cost-effective solution for freshness assessment (Mkhari et al., 2025).

The development of multi-analyte sensors capable of monitoring multiple spoilage indicators simultaneously remains a key research focus for improving reliability and accuracy.

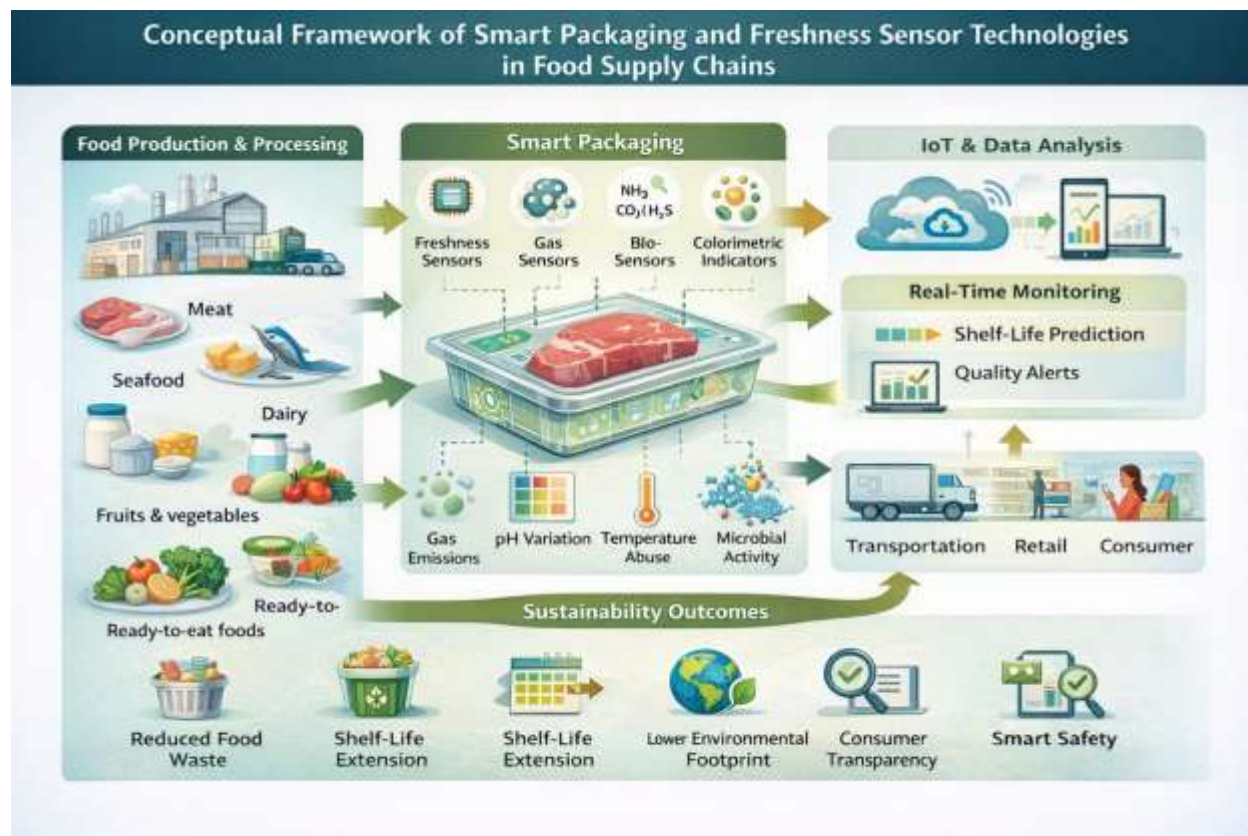


Figure 1. Conceptual Framework of Smart Packaging and Freshness Sensor Technologies in Food Supply Chains

The figure presents an integrated overview of smart packaging systems, highlighting key components such as freshness sensors, biosensors, gas indicators, and time-temperature indicators embedded within food packaging materials. Sensor mechanisms detect physicochemical changes, including gas emissions, pH variation, temperature abuse, and microbial activity associated with food spoilage. These signals are processed through intelligent systems and, in advanced applications, transmitted via Internet of Things (IoT) platforms for real-time monitoring and data analytics. The framework demonstrates the application of smart packaging from food production and processing to transportation, retail, and consumer use. Additionally, the figure emphasizes sustainability outcomes, including shelf-life extension, food waste reduction, improved resource efficiency, and enhanced consumer trust. This holistic representation highlights the role of smart packaging in improving food safety, supply chain transparency, and environmental sustainability.

4. Materials and Fabrication Technologies

Material selection is a foundational determinant of functionality, safety, and sustainability in smart packaging systems. Recent research increasingly emphasizes the transition from conventional petroleum-based plastics toward biodegradable polymers, bio-based films, and edible coatings that minimize

environmental impact while maintaining mechanical integrity and barrier properties (Soundara Rajan & Wani, 2025). These sustainable materials not only reduce plastic pollution but also enhance consumer acceptance and regulatory compliance, particularly in food-contact applications where safety and biodegradability are critical.

The incorporation of nanocomposites has significantly advanced the sensing performance of intelligent packaging. Materials such as metal nanoparticles, carbon nanotubes, graphene derivatives, and conductive polymers enhance electrical conductivity, sensitivity, and response time of freshness sensors. These nanostructured materials improve signal transduction and enable detection of spoilage-related gases, pH changes, and microbial activity under varying storage and distribution conditions (Bhatlawande et al., 2023). Additionally, nanocomposites contribute to improved mechanical strength and thermal stability, supporting sensor durability throughout the food supply chain.

Fabrication technologies play a key role in translating material innovations into scalable products. Printing-based approaches, including inkjet, screen, and roll-to-roll printing, are increasingly favored due to their cost-effectiveness, scalability, and compatibility with flexible substrates. These techniques allow precise and reproducible deposition of sensing layers and conductive tracks, enabling mass production of smart labels and indicators (Palanisamy et al., 2025). However, challenges related to material compatibility, sensor migration, and long-term food contact safety remain critical barriers to commercialization, necessitating continued research and regulatory evaluation (Davidescu et al., 2025).

5. Applications in Food Supply Chains

Smart packaging technologies have found wide-ranging applications across food supply chains, particularly in perishable products such as meat, seafood, dairy, fruits, and ready-to-eat meals. These systems enhance quality assurance by providing continuous, real-time freshness information from production through transportation, storage, and retail stages (Sangamesh et al., 2026). Such monitoring reduces uncertainty associated with product quality and supports more responsive supply chain management.

In temperature-sensitive food sectors, freshness sensors and time-temperature indicators enable dynamic shelf-life management by detecting temperature abuse and spoilage progression during distribution. This capability allows retailers to optimize inventory turnover, minimize product recalls, and reduce food waste (Doderio et al., 2021). Smart packaging also improves cold-chain transparency by offering actionable data that can be shared among logistics providers and food processors.

At the consumer level, intelligent indicators improve transparency and trust by enabling buyers to independently assess food quality without relying solely on static expiration dates. This shift empowers informed purchasing and consumption decisions, ultimately reducing household food waste (Soundara Rajan & Wani, 2025). Furthermore, integration with IoT platforms facilitates real-time data sharing and predictive analytics, enhancing traceability and decision-making across the supply chain (Sagar & Rani, 2026).

6. Sustainability and Food Waste Reduction

Smart packaging and freshness sensors contribute directly to global efforts aimed at reducing food loss and waste by providing accurate, product-specific freshness information. By distinguishing between spoiled and still-edible food, these technologies prevent premature disposal and promote more efficient use of resources throughout the supply chain (Davidescu et al., 2025). This targeted approach to freshness

assessment supports sustainability goals by reducing unnecessary production, transportation, and associated greenhouse gas emissions.

Dynamic freshness monitoring enables flexible distribution and pricing strategies, such as redirecting products nearing spoilage to alternative markets or offering timely discounts. These practices significantly reduce waste at retail and household levels while improving economic efficiency (Mkhari et al., 2025). In parallel, sustainable material innovations—such as biodegradable substrates and recyclable sensor components—strengthen the environmental benefits of intelligent packaging systems and align them with circular economy principles (Soundara Rajan & Wani, 2025).

Despite these advantages, challenges remain in balancing technological complexity with environmental impact. The incorporation of electronic components raises concerns related to electronic waste, recyclability, and lifecycle assessments. Addressing these issues will be essential to ensure that smart packaging solutions deliver net environmental benefits at scale.

7. Challenges and Future Research Directions

Although smart packaging technologies have advanced rapidly, several barriers continue to limit their widespread adoption. High production costs, regulatory uncertainties, and the lack of standardized testing protocols pose significant challenges for commercialization (Davidescu et al., 2025). These issues are particularly pronounced for small and medium-sized food producers, where cost sensitivity and regulatory compliance can restrict technology uptake.

Sensor performance can also be influenced by environmental variability and food matrix complexity, affecting accuracy and reliability. Further research is needed to improve sensor calibration, robustness, and long-term stability under real-world conditions (Mani et al., 2025). Additionally, the growing integration of digital technologies raises concerns related to data privacy, cybersecurity, and interoperability across platforms (Sagar & Rani, 2026).

Future research should focus on scalable manufacturing methods, multifunctional sensor systems, and regulatory-compliant materials that support both safety and sustainability. Interdisciplinary collaboration among food scientists, materials engineers, data scientists, and policymakers will be critical for translating laboratory-scale innovations into market-ready smart packaging solutions (Sangamesh et al., 2026).

8. Conclusion

Smart packaging and freshness sensor technologies represent a transformative approach to food quality monitoring, offering real-time, accurate, and accessible information across the food supply chain. Advances in materials, fabrication methods, and sensor integration have enabled intelligent packaging systems that enhance food safety, improve supply chain efficiency, and support sustainability objectives. Their application across diverse food categories demonstrates strong potential for reducing uncertainty in freshness assessment and minimizing food loss and waste.

However, achieving large-scale implementation will require addressing technical, economic, and regulatory challenges while ensuring environmental responsibility. Continued innovation, supported by interdisciplinary research and harmonized policy frameworks, will be essential for advancing smart packaging toward widespread commercial adoption. As these technologies mature, they are poised to play a vital role in creating more resilient, transparent, and sustainable global food systems.

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