Smart Packaging: Role of Sensors and Indicators in Assuring Food Safety and Quality Assurance

Sumiran Pandey[1], Akash Deep Shukla[2] and Sweta Rai[2]
[1]Department of Food and Nutrition, College of Community Science, GBPUAT, Pantnagar, Uttarakhand, India
[2]Department of Food Science and Technology, College of Agriculture, GBPUAT, Pantnagar, Uttarakhand, India
Corresponding Author: pandeysumi1997@gmail.com

1. Introduction

Freshness is a key indicator of food quality, directly influencing taste, texture, nutritional value, and safety. Spoiled foods may harbour harmful microorganisms and toxins, making freshness monitoring vital. Food packaging systems are primarily designed to preserve freshness, structural integrity, and shelf life. Continuous advances in packaging technology, conventional packaging has evolved into "smart packaging," which employs mechanisms to monitor changes within food products. Since foods are complex systems with diverse physical, chemical, and physicochemical needs, packaging must be tailored to suit these requirements. Smart packaging is broadly classified into two categories: intelligent packaging and active packaging (Drago et al., 2020). Intelligent packaging integrates traditional materials with sensing devices to detect quality changes, track storage conditions, and ensure safety prior to consumption. Active packaging, on the other hand, incorporates functional compounds such as antioxidants to enhance food stability and protect against spoilage throughout shelf life. While both approaches aim to improve safety and quality, but their mechanisms differ. Intelligent packaging provides real-time information, whereas active packaging directly interacts with food to prolong freshness. Electronic coding systems further strengthen traceability by enabling identification and monitoring at any point in the supply chain.

The market for active packaging is rapidly expanding, projected to grow at a CAGR of 6.62% from US$20.386 billion in 2019 to US$31.924 billion by 2026 (Research and Markets, 2021). Active packaging improves performance by adding functional elements that safeguard against contamination and extend shelf life. Intelligent packaging complements this by communicating changes in food condition, signalling issues such as temperature fluctuations, pH shifts, microbial activity, or volatile compound release (Kuswandi & Murdyaningsih, 2017). Beyond safety and quality, these technologies also support sustainability. Intelligent communication with packaging can reduce energy use in cold chains, limit the need for preservatives, and minimize food waste (Holman et al., 2018).

To design smart packaging, it requires to consider for commodity-specific spoilage factors. For example, oxidative rancidity in fat-rich products like biscuits, ethylene production in climacteric fruits, high water activity in beverages, and microbial and oxidative spoilage in meat products. Thus, smart packaging provides an adaptable framework for improving food quality, safety, and sustainability while addressing the distinct preservation needs of different food categories.

2. Sensors and indicators in intelligent food packaging

Sensors are instruments designed to measure and characterize the chemical or physical properties of substances and their environment, thereby providing real-time information on food quality and safety (Ghaani et al., 2016). A typical analyte sensor comprises four components: a receptor that binds to the target analyte and induces a measurable change; a transducer that converts this change into a signal; a device for signal processing; and a visual display (Selvolini & Marrazza, 2023). There are various conventional techniques for food quality assessment, such as sensory evaluation, microbial testing, and instrumentation-based analysis like HPLC and GC–MS. These are accurate but they are also time-consuming, costly, and require skilled personnel (Vinoth, Karthika et al., 2024; Vinoth, Tammina et al., 2024; Zhang et al., 2019). Intelligent food packaging (IFP) equipped with sensors provides a more efficient, non-invasive alternative by monitoring freshness and safety throughout the supply chain without disturbing the package (Ghaani et al., 2016).

IFP incorporates active or passive sensors into packaging substrates such as films, labels, caps, or wrappers. Active sensors require external readers or activation to record measurements, whereas passive sensors respond autonomously to analytes or environmental changes through irreversible optical, electrical, or chemical shifts (Sharma et al., 2022). Both enable continuous, non-destructive monitoring without compromising barrier properties (Ghoshal, 2018). Depending on design, sensors may be positioned inside the package, where they detect spoilage gases, pH, or temperature abuse; or externally, to track conditions such as temperature and humidity during transport (Kuswandi et al., 2022). Freshness sensors function by detecting compounds linked to spoilage or by indirectly monitoring environmental variables associated with deterioration. They can operate as direct-contact devices, such as gas and pH sensors, or as non-contact systems like time–temperature indicators, humidity sensors, and RFID tags (Mustafa & Andreescu, 2018). Sensor-enabled smart packaging plays a crucial role in ensuring food safety, integrity, and consumer trust by extending shelf life and minimizing waste.

3. Sensor Types in Intelligent Food Packaging

Intelligent food packaging systems utilize various sensors to monitor food quality and safety and provide real-time data and alerts to consumers, retailers, and producers

(Ghaani et al. 2016). Each type of sensor plays a specific role in detecting changes that may indicate spoilage, contamination, or spoilage conditions.

3.1 Gas Sensors

Gas sensors are an integral component of intelligent food packaging systems, designed to detect spoilage-related gases such as carbon dioxide (CO_2), oxygen (O_2), ethylene, and volatile organic compounds (VOCs) (Matindoust et al., 2021; Li et al., 2020). Elevated CO_2 levels often signal microbial spoilage in meat, while ethylene detection is important for monitoring the ripening of fruits and vegetables (Vinoth, Karthika et al., 2024; Vinoth, Tammina et al., 2024). These sensors employ different mechanisms, including electrochemical, metal oxide semiconductor, and photoacoustic spectroscopy, and provide real-time feedback that helps extend shelf life, reduce food waste, and enhance consumer safety and trust. The effectiveness of a gas sensor depends on parameters such as sensitivity, selectivity, limit of detection (LOD), response time, and recovery time. Ideally, a sensor should respond rapidly to changes in gas concentration, recover quickly, and show high selectivity toward the target gas while minimizing interference (Nami et al., 2024).

Challenges such as hysteresis, where the response does not return to baseline, and signal drift, where outputs shift over time under constant conditions, can compromise accuracy. These issues may arise from surface chemistry changes, environmental fluctuations, or sensor degradation, and are often mitigated through calibration, environmental controls, and correction algorithms (Korotcenkov & Cho, 2010; Palmé et al., 2011, Mustafa et.al 2018).

3.2 pH Sensors

pH sensors are essential components of intelligent food packaging systems, as they monitor acidity or alkalinity changes that often signal microbial growth and spoilage (Liu, Jin et al., 2024; Liu, Zheng et al., 2024). Perishable foods such as meat, dairy, and seafood undergo pH shifts due to microbial metabolism, which can be detected by pH-sensitive electrodes or materials, providing real-time insights into product quality and safety (Poghossian et al., 2019; Jothi & Rhim, 2024). By detecting abnormal pH levels, these sensors help extend shelf life, reduce waste, and prevent foodborne illness. Emerging techniques such as, fluorometric pH sensing has attracted attention for its non-invasive and real-time monitoring capability (Bigdeli et al., 2019). Fluorescent probes, widely applied in biological studies, exploit the optical properties of organic dyes to sensitively track pH changes. However, issues such as photobleaching, probe concentration, and environmental interference can affect measurement accuracy (Ji et al., 2022). To overcome these limitations, ratiometric sensing that uses emission intensity ratios at different wavelengths, offers improved stability and reliability (Youssef et al., 2023).

Recent research has advanced ratiometric fluorescent pH sensors, including systems based on silica nanoparticles embedded with fluorophores like fluorescein and rhodamine B. Such designs achieve wide detection ranges (pH 4–8), high accuracy, and biocompatibility, with applications extending beyond food monitoring to cellular studies, such as tracking mitochondrial and lysosomal pH changes during mitophagy (Zhang et al., 2022; Ding & Hong, 2020). While many of these systems are still at the experimental stage, their adaptability suggests strong potential for integration into food packaging to monitor freshness in real time.

3.3 Biosensors

Biosensors in intelligent food packaging use biological elements such as enzymes, antibodies, or nucleic acids to detect pathogens and toxins by converting biological interactions into measurable signals (Upadhyayula 2012). Integrated with electronic systems, they enable real-time monitoring, helping to prevent contaminated food from reaching consumers (Sargazi et al. 2022; de Jonge et al. 2004). Fluorescent biosensors, particularly those using metal oxide nanozymes, show strong potential due to their ability to amplify signals and provide rapid detection (Mahmudunnabi et al. 2020). Examples include MnO_2–graphene quantum dot systems for acetylcholinesterase detection (Yan et al. 2016), V_2O_5 nanoribbon–carbon dot systems for ascorbic acid and enzyme detection (Ansari et al. 2021), and Fe_3O_4–CdTe quantum dot systems for glucose measurement (Liu et al. 2015).

3.4 Temperature Sensors

Temperature sensors are vital in intelligent food packaging, ensuring that products are stored and transported within safe temperature ranges to prevent spoilage and pathogen growth (Kalpana et al. 2019; Matindoust et al. 2016). Common types include thermocouples, thermistors, and infrared sensors, which can be integrated with electronic systems to provide real-time alerts when deviations occur (Chen et al. 2020). Time–temperature integrators (TTIs) offer cost-effective, non-destructive monitoring of temperature history, making them essential for cold-chain management (Manjunath Shetty 2018; Koutsoumanis & Gougouli 2015). RFID-enabled sensors further enhance monitoring by enabling wireless tracking and data communication (Fattori et al. 2020; Valderas et al. 2023). Innovations such as 'Evigence', TTIs provide visual and digital readouts through irreversible color-change reactions, allowing reliable, real-time assessment of food safety and shelf-life throughout production and distribution (Osmólska et al. 2022).

3.5 Humidity Sensors

Humidity sensors in intelligent food packaging help maintain optimal moisture levels to prevent microbial growth, texture loss, and spoilage (Hao et al. 2025; Cheng et al. 2022). They are particularly important for baked goods, fresh produce, and dried foods, where excess or insufficient moisture can compromise quality and shelf life (Pereira de Abreu et al. 2012). Most humidity sensors rely on hygroscopic polymers, capacitive elements, or nanocomposites that alter their electrical properties in response to moisture (Puligundla et al. 2012). When integrated with monitoring systems, they provide real-time data, trigger alerts, or activate humidity control mechanisms (Dodero et al. 2021). Recent advances include biodegradable IDE-based sensors, PVC–graphene oxide nanocomposites, and flexible printed sensors using graphene oxide-supported $MoTe_2$ nanosheets, all offering high sensitivity and eco-friendly performance (Balbinot-Alfaro et al. 2019; Wawrzynek et al. 2021; Gopalakrishnan et al. 2022). Such technologies are particularly valuable for packaging cereals, snacks, and powders where moisture control is critical (Osmólska et al. 2022).

3.6 Optical Sensors

Optical sensors employ light-based techniques such as fluorescence and infrared spectroscopy to monitor food quality and detect spoilage, oxidation, or microbial contamination (Beshai et al. 2020). Fluorescence sensors measure changes in emitted light that signal microbial or chemical activity, while infrared sensors assess composition, moisture, and freshness through absorption patterns (Mohammadpour & Naghib 2021). These non-invasive, real-time systems can be integrated with digital platforms to alert stakeholders when food quality declines, enabling early intervention, improving safety, and reducing waste (Wu et al. 2021).

4. Indicators types in intelligent food packaging

1. **Freshness indicators:** These provide consumers information about the product's quality and freshness by detecting changes in gas composition or pH levels within the package. Spoilage of food results in release of gases like CO_2 or pH changes, intelligent packaging system equipped with gas sensors monitor the concentration of these gases. (Liu Jin et.al 2024)
2. **Spoilage detection:** Detecting food spoilage early is a key feature of intelligent packaging systems, helping to identify signs of deterioration before they are visible to consumers (Kalpana et al., 2019). These systems often use sensors to detect gases like ammonia and hydrogen sulfide, which result from microbial activity and chemical changes in food (Dodero et al., 2021). Ammonia commonly indicates protein breakdown in items like meat and seafood, while hydrogen sulfide signals bacterial activity in products such as dairy and canned foods. Advanced gas sensors such as metal oxide semiconductors based or selective electrodes based, can detect even small amounts of these spoilage gases (Firouz et al., 2021)
3. **Pathogen detection:** Pathogen detection represents a vital function of biosensors in intelligent food packaging, aimed at safeguarding consumers from harmful microorganisms such as *E. coli*, *Salmonella*, and *Listeria*. These biosensors employ biological recognition elements like antibodies, enzymes, or nucleic acids to selectively identify and detect pathogenic organisms present in food (Maishu and Atemenkeh 2022). For instance, antibody-based biosensors are specifically engineered to recognize antigens unique to particular bacteria. When these pathogens interact with the sensor, a detectable response such as a visible color shift or electrical signal is produced (Khan et al. 2024).

5. Consumer perception of smart packaging technology

Consumer perceptions toward conventional and smart packaging technologies were neutral toward existing food packaging, while a smaller proportion expressed dissatisfaction (Li et al., 2020). Conventional packaging was viewed as inadequate for meeting modern consumer demands, creating opportunities for the adoption of smart packaging. Such systems provide greater product information, facilitate purchasing decisions, and support more efficient consumption, storage, and disposal (Plimmer, 2013). Despite this potential, awareness remains limited. Only 17% of consumers were familiar with the term "smart packaging," though many showed interest in learning more and adopting it (Daoud and Trigui, 2019; O'Callaghan & Kerry, 2016).

6. Conclusion

Intelligent food packaging equipped with advanced sensors offers a modern solution for improving food safety, quality control, and reducing waste by monitoring parameters like temperature, humidity, gas levels, and pathogens in real time. Despite its potential, high costs, scalability issues, and limited sensor sensitivity hinder large-scale use. Future efforts should focus on developing affordable, biodegradable materials and adaptable sensors, along with integrating IoT technologies to enhance traceability and data analysis. Collaboration among researchers, industry, and policymakers is essential to address these challenges. With continued innovation, intelligent packaging can greatly enhance food safety, sustainability, and consumer confidence.

References

Ansari, L., S. Hallaj, T. Hallaj, and M. Amjadi. 2021. "Doped-Carbon Dots: Recent Advances in Their Biosensing, Bioimaging and Therapy Applications." *Colloids and Surfaces B: Biointerfaces* **203**: 111743.

Ahmed, I., H. Lin, L. Zou, et al. 2018. "An Overview of Smart Packaging Technologies for Monitoring Safety and Quality of Meat and Meat Products." *Packaging Technology and Science* **31**, no. 7: 449–471.

Kuswandi, Bambang & Wicaksono, Yudi & Jayus, Jay & yook heng, Lee & Musa, Ahmad. (2011). Smart Packaging: Sensors for monitoring of food quality and safety. Sensing and Instrumentation for Food Quality and Safety. 5. 137-146. 10.1007/s11694-011-9120-x.

Mani, R., Kumar, J.V., Murugesan, B., Alaguthevar, R. and Rhim, J.-W. (2025), Smart Sensors in Food Packaging: Sensor Technology for Real-Time Food Safety and Quality Monitoring. J Food Process Eng, 48: e70120.

Bhargava, N., V. S. Sharanagat, R. S. Mor, and K. Kumar. 2020. "Active and Intelligent Biodegradable Packaging Films Using Food and Food Waste-Derived Bioactive Compounds: A Review." *Trends in Food Science & Technology* **105**: 385–401.

Thirupathi Vasuki, M., Kadirvel, V., & Pejavara Narayana, G. (2023). Smart packaging—An overview of concepts and applications in various food industries. *Food Bioengineering*, 2, 25–41.

Chen, H.-Z., M. Zhang, B. Bhandari, and C.-H. Yang. 2019. "Development of a Novel Colorimetric Food Package Label for Monitoring Lean Pork Freshness." *LWT- Food Science and Technology* **99**: 43–49.

Choudhary, S., B. Joshi, G. Pandey, and A. Joshi. 2019. "Application of Single and Dual Fluorophore-Based pH Sensors for Determination of Milk Quality and Shelf Life Using a Fiber Optic Spectrophotometer." *Sensors and Actuators B: Chemical* **298**: 126925.

Escher, A., H. Megahd, C. Tavella, D. Comoretto, and P. Lova. 2023. "Colorimetric Polymer Sensors for Smart Packaging." *Macromolecular Chemistry and Physics* **224**, no. 14: 2300022.

Firouz, M. S., K. Mohi-Alden, and M. Omid. 2021. "A Critical Review on Intelligent and Active Packaging in the Food Industry: Research and Development." *Food Research International* **141**: 110113.

Liu, T., N. Zheng, Y. Ma, et al. 2024. "Recent Advancements in Chitosan- Based Intelligent Food Freshness Indicators: Categorization, Advantages, and Applications." *International Journal of Biological Macromolecules* 275: 133554.

Kalpana, S., S. R. Priyadarshini, M. M. Leena, J. A. Moses, and C. Anandharamakrishnan. 2019. "Intelligent Packaging: Trends and Applications in Food Systems." *Trends in Food Science & Technology* 93: 145–157.

Firouz, M. S., K. Mohi- Alden, and M. Omid. 2021. "A Critical Review on Intelligent and Active Packaging in the Food Industry: Research and Development." *Food Research International* 141: 110113.

Dodero, A., A. Escher, S. Bertucci, M. Castellano, and P. Lova. 2021. "Intelligent Packaging for Real- Time Monitoring of Food Quality: Current and Future Developments." *Applied Sciences* 11, no. 8: 3532.

Maishu, S. P., and N. C. Atemenkeh. 2022. "Applications of Nanosensors as Pathogen Detectors in Packaged Food." In *Nanotechnology in Intelligent Food Packaging*, edited by T. B. Annu and S. Ahmed, 291–312. Scrivener Pub.

Khan, S., J. K. Monteiro, A. Prasad, C. D. Filipe, Y. Li, and T. F. Didar. 2024. "Material Breakthroughs in Smart Food Monitoring: Intelligent Packaging and On- Site Testing Technologies for Spoilage and Contamination Detection." *Advanced Materials* 36, no. 1: 2300875.

* * * * * * * * *