

## Recent advances in intelligent packaging technologies for real-time food quality monitoring: A comprehensive review

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### Abstract

The rising global demand for safer, fresher and more sustainable food products has catalysed rapid advancements in intelligent packaging technologies. This review comprehensively explores intelligent packaging systems as a transformative innovation in food packaging, aimed at improving food safety, quality assurance and supply chain transparency. Intelligent packaging integrates functional components such as indicators, sensors, biosensors and data carriers (*e.g.*, RFID) that interact with food and its environment to monitor and communicate real-time information on freshness, spoilage and storage conditions. Among the intelligent packaging technologies examined, time-temperature indicators (TTIs), freshness indicators, gas sensors, and biosensors have demonstrated considerable potential for monitoring food quality through the detection of key changes associated with product deterioration, including temperature variation, microbial proliferation, pH alteration, and the release of volatile compounds. This review summarizes commercially available systems, highlighting their operating principles as well as their application-specific benefits and constraints. It also discusses major barriers to broader industrial implementation, such as economic limitations, concerns regarding sensor safety, technical integration issues, and limited consumer acceptance. By evaluating recent technological advances and identifying existing knowledge gaps, the review offers an updated perspective for researchers, industry professionals, and policymakers, supporting the development and commercialization of advanced intelligent packaging systems that enhance food safety, environmental sustainability, and consumer confidence.

**Key words:** biosensors, food safety, freshness indicators, intelligent packaging, time-temperature indicators

### Introduction

Packaging is an art, science and technology that ensures the quality, wholesomeness, integrity and safety of products. The supply chain involves preparing items for transportation, distribution, storage, sale and usage. It not only ensures safe product delivery to consumers but also optimizes delivery costs and sales (Pal *et al.*, 2019). Packaging serves four main functions: convenience, protection, communication and confinement. The packaging communicates with consumers through written language or pictures and simplifies product handling through practical features such as reclosability and microwavability. It provides a variety of container shapes and sizes to accommodate customers' lifestyles (Yam and Lee, 2012). Packaging not only improves marketing and distribution, but also reduces quality degradation and they play a vital role in ensuring the safety and preservation of packaged food (Dobrucka, 2013). However, total eradication of quality loss by packaging is not feasible. The intrinsic qualities of very perishable foods are mostly altered following processing. This can either improve quality (*e.g.*, fruit ripening) or reduce it. Product spoiling can occur due to biological, chemical or physical processes within the package (Heising *et al.*, 2014).

Food packaging is an integral part of the food supply chain, helping to protect products from physical damage during handling and transportation, as well as from contamination and other external factors that may affect quality and safety (Muller and

Schmid, 2019). It also helps maintain product integrity by keeping the package sealed throughout distribution until it reaches the consumer, thereby minimizing leakage and reducing the risk of tampering. Beyond its protective function, packaging serves as an important medium of communication between manufacturers and consumers by providing essential product information, including nutritional composition, health-related claims, instructions for use and storage, country of origin, manufacturing and expiry dates, best-before dates, and other details that assist consumers in making informed purchasing decisions (Sohail *et al.*, 2018).

Despite more advancements in food packaging technologies, microbial contamination remains a major hurdle affecting food safety and shelf life (European Commission, 2009). The packaging industry has the mandate of designing modern, trustworthy packaging systems to meet the rising demand by consumers for fresh food with longer shelf life and consistent quality (Cierpiszewski, 2016). Such solutions should enhance the packaging material properties, such as gas barrier characteristics, ultraviolet protection, transparency, and the environment. Temperature, oxygen level, relative humidity, carbon dioxide level, and moisture content play a significant role in influencing food quality, safety, and shelf life; this necessitates monitoring of such factors in real-time (Abreu *et al.*, 2012). Industry growth is being driven by new packaging technologies, specifically through the creation of intelligent packaging systems. Intelligent packaging combines sensing and communication technology

with conventional packaging, offering critical information on both internal and external changes on the product. Such systems communicate with the product and its environment to enhance shelf life, safety, and sensory qualities. Experts predict that future generations of intelligent packaging will significantly influence food packaging by providing new ways of ensuring product quality and safety (Ghaani *et al.*, 2016). This review provides a modern synthesis of smart packaging science to academicians, researchers, and manufacturers. The aim is to highlight essential research needs and determine barriers to commercial adoption of such technologies. Through the provision of a modern knowledge base, this research will guide future research and enable the effective deployment of advanced packaging solutions.

Although the terms active packaging, intelligent packaging and smart packaging are often used interchangeably, they represent distinct concepts within modern food packaging systems. Active packaging is designed to interact directly with the packaged food or its surrounding environment to extend shelf life and maintain product quality through mechanisms such as oxygen scavenging, moisture absorption, antimicrobial release and ethylene removal. In contrast, intelligent packaging does not actively modify the packaged environment but instead monitors, detects and communicates information regarding the condition of the food, package integrity or storage environment using devices such as time-temperature indicators, freshness indicators, gas sensors, biosensors and radio-frequency identification (RFID) systems. Smart packaging is a broader concept that integrates both active and intelligent packaging functionalities, enabling simultaneous preservation and monitoring of food products. By combining quality enhancement with real-time or near-real-time information exchange, smart packaging offers an advanced solution for improving food safety, traceability, quality assurance and supply-chain management (Abreu *et al.*, 2012).

Regarding the underlying principles and uses, numerous scholars have variously defined the term. Intelligent packaging is generally defined as a system that incorporates several intelligent methods to make choices to detect damage or spoilage, enhance quality, increase shelf life and provide information. (Yam *et al.*, 2005). The concept of intelligent packaging, that is, enhancing the quality and value of foodstuffs by undertaking various intelligent functions tracking the journey of the product along the supply chain, displaying pertinent product details, and assessing the safety and quality conditions surrounding the product, has been of significant concern to the food packaging sector (Yam *et al.*, 2005).

A control system that can carry out intelligent tasks like standby, detection, tracking, recording and communication is known as intelligent packaging. Its purpose is to give particular parameters to each link in the packaging chain, such as manufacturers, distributors, salespeople and customers. The package will contain information regarding the product's history (storage conditions, headspace composition, microbiological growth, *etc.*) in addition to the product itself (origin, composition and theoretical expiry date). Therefore, reducing food waste and improving food logistics and traceability are made possible by the use of intelligent packaging (Wang *et al.*, 2018).

**Literature search strategy:** A literature search was performed using Scopus, Web of Science, ScienceDirect, SpringerLink and Google Scholar for studies published between 2005 and 2025. Keywords included “intelligent packaging,” “smart packaging,” “active packaging,” “food quality monitoring,” “freshness indicators,” “time–temperature indicators,” “biosensors,” “gas sensors,” “RFID,” and “food safety.” Peer-reviewed articles were preferred, but relevant reviews, conference papers and industry reports were also considered. Unrelated and low-evidence studies were excluded as duplicates. Studies were selected and then classified into indicators, sensors, biosensors, gas sensors, and RFID systems and analysed on their principles, applications, advantages, disadvantages and commercial prospect.

### Indicators

An indicator is a device that provides a customer with information on food quality, microbial activity and other attributes. It functions according to certain features, such as the existence or lack of a target chemical or biological substance, the strength of the reaction(s) between two or more substances, or the variation in chemical concentration in food as indicated by an obvious and irreversible color shift or movement of color borders (Ghoshal, 2018). Indicators may be classified as external indicators, which are placed outside the package, and internal indicators, which are incorporated inside the package or headspace. (Pavelkova, 2013).

**Temperature indicator:** These are the type of indicators that respond to variations in the product's or the product's container's temperature. These indicators are often economical and environmentally beneficial, and they measure and show temperature (Barska and Wyrwa, 2017).

**Critical temperature indicators:** Only demonstrate that a product was exposed to an incorrect temperature for a certain amount of time when it was exposed to abnormal temperature ranges (below or above the critical temperature of storage) for a

Table 1. Commercial TTIs system used in food packaging applications (Kalpana *et al.*, 2019).

TTI commercial name	Developer	Principle	Applications
3M™ MonitorMark®	3M	Molecular diffusion of colored dye-based ester into viscous material matrix	Bakery, beverage, confectionary products
Fresh-Check®	Temptime Corporation	Central part of the label is the most active/reactive part; on reaction ( <i>i.e.</i> at higher temperature), darkens irreversibly at an accelerated rate	Vegetables and fruits products
Smart dot	EVIGENCE SENSORS™	Indicator changes color from green to red when exposed to temperature	Bakery and frozen food products
WarmMark®	DeltaTrak	A blotter paper pad saturated with a red-dyed chemical is specially formulated to melt at the tag's response temperature	Temperature monitoring during processing, storage and transportation
Cold Chain iToken™	DeltaTrak	Smart barcode system tracks cumulative temperature above threshold value; irreversible barcode change provides discrete temperature data	Cold chain management
OnVu™	EVIGENCE SENSORS™	Activated with UV light source, the dark color of TTI progressively becomes lighter with change in temperature;	Dairy products
Keep-it®	Keep-it Technologies	Polymerization reaction TTI	Bakery, beverage, confectionary products
TopCryo®	TRACEO	Microbiological TTI	Cold chain management

longer period of time than was necessary to affect the product's safety or quality adversely. These kinds of indicators can be used to safeguard goods whose qualities alter irrevocably even after a single exposure to a crucial temperature: For instance, frozen goods (Barska and Wyrwa, 2017).

**Critical temperature/time indicators:** These indicators track the history of temperature changes relative to a specified threshold, indicating whether the ambient temperature has exceeded that

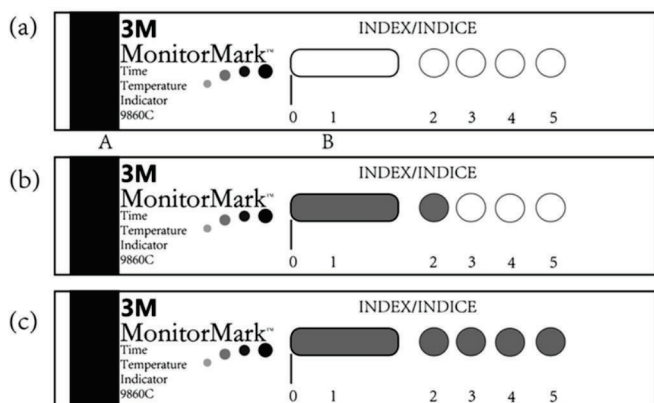


Fig. 1. Discoloration process of Monitor Mark™ time temperature indicators. (a) The color of the indicator when activated. (b) The color of the indicator during operating process. (c) The final state of the indicator after fully exposed (Wang *et al.*, 2015).

threshold. Consequently, they reflect the amount of energy applied to the indicator, which corresponds to the temperature above the threshold at which chemical reactions cause a change in the indicator's color and the moment this threshold is crossed (Giannoglou *et al.*, 2014). Such indicators are useful for monitoring the storage conditions of products that undergo significant changes in their properties once a certain temperature is reached. The primary reason for these changes is often an increase in the rates of enzymatic, chemical, and microbiological processes (Singh *et al.*, 2018).

**Time-temperature indicators:** Time and temperature indicators (TTIs) are easy-to-use and reasonably priced sensors that track a food package's temperature across the course of packing, storage, transport and retailing. The most widely utilized indicators in food packaging are TTIs. Two forms of these indicators exist: temperature indicators and time temperature indicators (Nowacka and Fijałkowska, 2014).

Temperature monitors are used to register the temperature of a product all the time. They are very sensitive to changes in temperature and will even indicate a small increase or decrease in temperature that is not safe to store products. The packaging, or part of it, typically changes color when the temperature is too

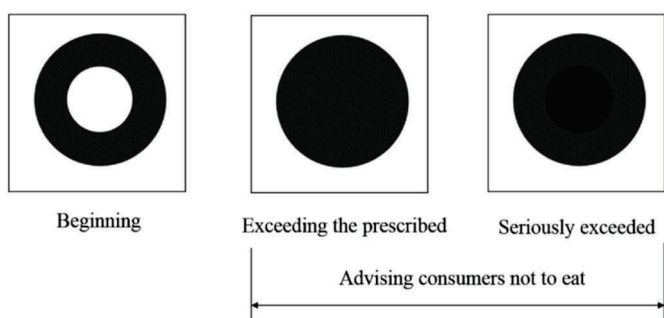


Fig. 2. Schematic illustration for the indication of Fresh-Check® (Gu *et al.*, 2002).

high. They are very crucial for chilled and frozen foods. They help show whether food is starting to thaw by changing color (Fig.1) (Singh *et al.*, 2018).

TTIs function by sensing changes in food products with respect to time and temperature. This can be mechanical, chemical, electrochemical, enzymatic, or microbiological (Gao *et al.*, 2020). For instance, chemical or physical responses to time and temperature is polymerization or acid-base reactions. Biological response is based on changes caused by biological agents, including spores, enzymes, or microbes, with regard to time and temperature (Pereira *et al.*, 2015). Such changes are normally shown as visible reactions, such as color or shape change (Dobrucka and Cierpiszewski, 2014). Since the indicators are normally fixed outside the package and do not come into contact with the food, they measure the temperature on the package surface and not the food (Pavelkova, 2013).

**Fresh-Check® indicator:** Fresh-Check® is a commercially available time-temperature indicator (TTI) designed to monitor cumulative temperature exposure during storage and distribution (Fig. 2). The indicator consists of two concentric circles, with the central circle containing a temperature-sensitive polymer and the outer circle serving as a reference. Exposure to elevated temperatures initiates polymerization reactions within the central region, causing a gradual darkening that reflects the decline in product quality over time (Nopwinyuwong *et al.*, 2010). The extent of this colour development is associated with a decrease in light reflectance and provides a visual estimate of the remaining shelf life. Once the central circle becomes darker than the surrounding reference ring, the product is considered to have reached the end of its acceptable storage period. To avoid unintended activation before application, Fresh-Check® indicators are typically stored at -24°C (Navrotskaya *et al.*, 2022). Product freshness can be assessed by comparing the colours of the two circles: a lighter central circle indicates a fresh product, similar colours suggest that the product remains suitable for consumption but has limited remaining shelf life, whereas a

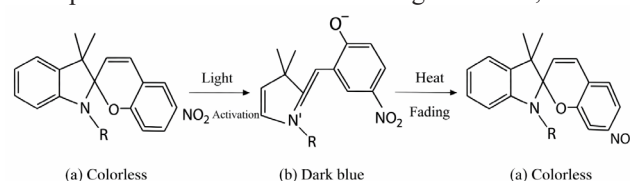


Fig. 3. Interconversion between (a) and (b) of OnVu™ indicator. Ultraviolet light exposure induces coloration while heat promotes the reverse reaction (Lv *et al.*, 2012).



Fig. 4. The indication and application of novel OnVu™ TTI.

darker central circle may indicate significant quality deterioration and reduced freshness assurance (Kerry *et al.*, 2006).

**Monitor Mark®:** is a time–temperature indicator (TTI) that provides a visual record of temperature abuse through the appearance of a blue colour on a white background once a predetermined temperature threshold is exceeded. This response results from the melting and subsequent diffusion of a fatty acid ester containing a blue dye, a process that can occur over a temperature range of approximately  $-15^{\circ}\text{C}$  to  $26^{\circ}\text{C}$ . The degree of blue colour development increases with the duration of exposure, allowing the indicator to reflect cumulative temperature history (Chen *et al.*, 2020).

**Keep-it® Fresh:** Unlike threshold-based indicators, Keep-it® Fresh functions as a full-history TTI that continuously records temperature exposure over time. Its operation is based on a chemical reaction between immobilized ferric ions ( $\text{Fe}^{3+}$ ) and mobile ferrocyanide ions. Activation occurs after removal of the protective seal, enabling the reactants to interact and generate a colour change that progresses according to both temperature and exposure duration (Yousefi *et al.*, 2019).

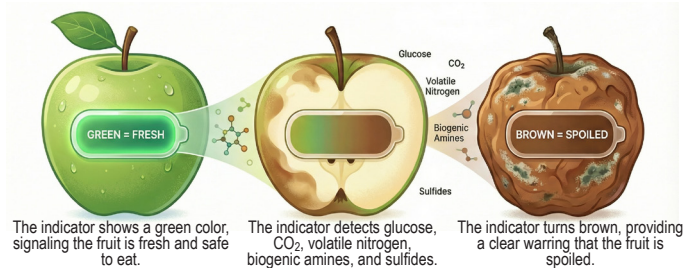


Fig. 5. A colorimetric freshness indicator's schematic operational mode.

**OnVu™:** The OnVu™ time-temperature indicator (TTI) from Ciba and Freshpoint™ is a photochemical reaction system based on benzopyridine pigments, which are color-changing pigments that change color over time at rates that are temperature-dependent. Initiated by ultraviolet (UV) light, the indicator is first dark blue and then fades with the elapse of time, allowing real-time estimation of product freshness (Kerry *et al.*, 2006). The system can be used either as a label or as a direct print onto the package. The ink in the OnVu™ TTI (Fig. 3) contains a photochromic compound, a reference color, a substrate, and a UV filter. The shape of the indicator is apple-shaped, with a colored core and a transparent outer shell. The aqua-based ink is in two states within the core: state (a) (Fig. 4), where the spiropyran is colorless and heat-stable, and state (b), where the spiropyran is blue and metastable. UV light exposure triggers the collapse from state (a) to (b), and with cycling of the temperature, the compound slowly returns from blue to colorless (Wang *et al.*, 2003). The

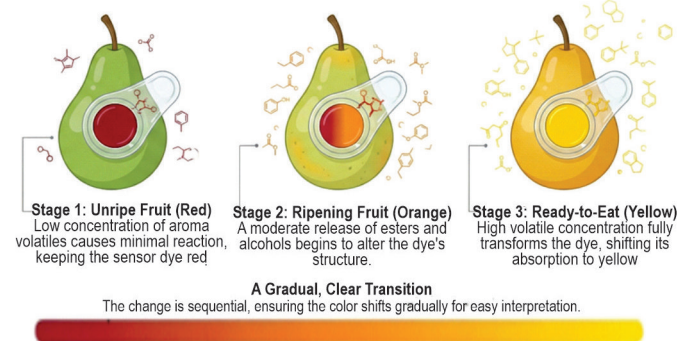


Fig. 6. Color transition of fruit ripeness indicator (Ripesense®) that reacts to aroma compounds, changing from red to orange to yellow in pears. (Kim *et al.*, 2018).

system is considered to be expired when the color of the core is the same as that of the colorless shell. The slow color change is a visual indicator of the freshness of the product and shelf life.

**Freshness indicators:** Unlike time–temperature indicators, freshness indicators provide information on the actual quality status of a food product by responding to compounds generated during spoilage (Zhai *et al.*, 2020). Microbial activity during storage leads to changes in the food matrix, including shifts in pH and the formation of metabolites associated with deterioration. These changes induce visible colour responses in the indicator, allowing consumers and retailers to assess freshness in a direct and practical manner (Fang *et al.*, 2017). Freshness indicators can detect a range of spoilage-related substances, including glucose, ethylene, carbon dioxide, volatile organic compounds, and metabolites produced during respiration and microbial growth. The resulting colour variation serves as a visual signal of quality changes occurring within the packaged product (Fig. 5) (Almasi *et al.*, 2022).

For commercial application, freshness indicators should be reliable, economical, easy to interpret, and adaptable to different food products. Among the available systems, colourimetric indicators have received considerable attention because of their simplicity and ease of use, leading to the development of products such as Freshcode®, Freshtag®, and Ripesense® (Becerril *et al.*, 2021). In fruit, vegetable, and dairy packaging, pH-sensitive dyes are commonly employed since microbial spoilage is often accompanied by changes in pH, resulting in a measurable colour response (Alizadeh-Sani, 2020). Ripesense® is a commercially available ripeness indicator designed for fruit products. It responds to aroma compounds released during ripening and exhibits a progressive colour transition from red to orange and finally yellow. At present, the technology has been commercialized primarily for pear packaging (Kim *et al.*, 2019) (Fig. 6).

### Sensors

Sensors are devices that detect physical, chemical or biological changes and convert them through a transducer into measurable signals, they are divided into active and passive categories based on the kind of transducer. In order to detect common analytes such as pH, humidity, color and biological species, chemical and biosensors are used as intelligent packaging tools (Mahalik and Nambiar, 2010). Edible sensors offer a novel approach in food packaging by providing a non-destructive method for spoilage detection (Su *et al.*, 2011). For example, a pectin-based edible sensor combines the principle of colorimetric changes of anthocyanins (from red cabbage extract) and variations in total volatile basic nitrogen to indicate spoilage (Dudnyk *et al.*, 2018). Similarly, a membrane film sensor was developed to monitor golden pomfret fillet freshness through pH variations detected by a fluorescent dye, offering a non-toxic solution for food packaging

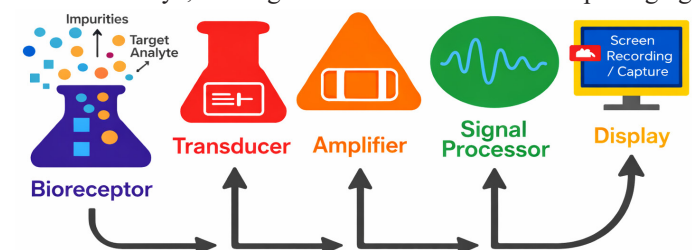


Fig. 7. Principle mechanism of smart sensors detecting food spoilage.

applications (Kiryukhin *et al.*, 2018). Optical colorimetric sensors, made by immobilizing pH-sensitive dyes into food-grade silicone matrices, can detect ammonia and biogenic amines and thereby assess food freshness (Schaude *et al.*, 2017).

**Biosensors:** A biosensor is an analytical instrument consisting of a bio-diagnostic component to convert bio-response into an electrical signal that can be measured. The instruments can be categorized based on the operating principles, including electrochemical biosensors (Hansen *et al.*, 2006), optical biosensors, immobilized biosensors, piezoelectric biosensors, microbial biosensors, and nanomaterial-based biosensors. A typical biosensor consists of three parts: a substrate made up of polymers, glass, metal or paper, a bio receptor, which may consist of enzymes, antibodies, cellular entities, nucleic acids, bacteriophages, or biomimetic components and a transducing unit (Adley, 2014). Biosensors can detect a broad spectrum of substances, including aflatoxin M1 in milk and milk products, broad-spectrum antibiotics, *Escherichia coli*, *Micrococci spp.*, *Listeria spp.* and urea (Thapar *et al.*, 2017) (Fig. 7). Initially, the

bio receptor identifies the target analyte. The transducer system converts the biological reactions into corresponding electrical signals. The transducer's weak signal is amplified, resulting in a larger output signal that retains the primary waveform characteristics of the input signals. Finally, the signal processor converts these signals into formats that can be recorded, stored, displayed, and analyzed (Mohammadi and Jafari, 2020).

**Gas sensors:** Gas sensors are used to monitor gaseous and volatile compounds associated with food quality and spoilage, including carbon dioxide, oxygen, volatile amines, and other target analytes. Among the available technologies, certain carbon dioxide sensors employ solid-state polymeric opto-chemical systems containing phosphorescent Pt-porphyrin and  $\alpha$ -naphtholphthalein as indicator dyes. The sensing mechanism relies on Förster resonance energy transfer (FRET), enabling the quantification of CO<sub>2</sub> concentrations. Despite their effectiveness, concerns have been raised regarding the potential migration of dye components, which may limit their suitability for food-packaging applications. Alternative CO<sub>2</sub> sensing systems have

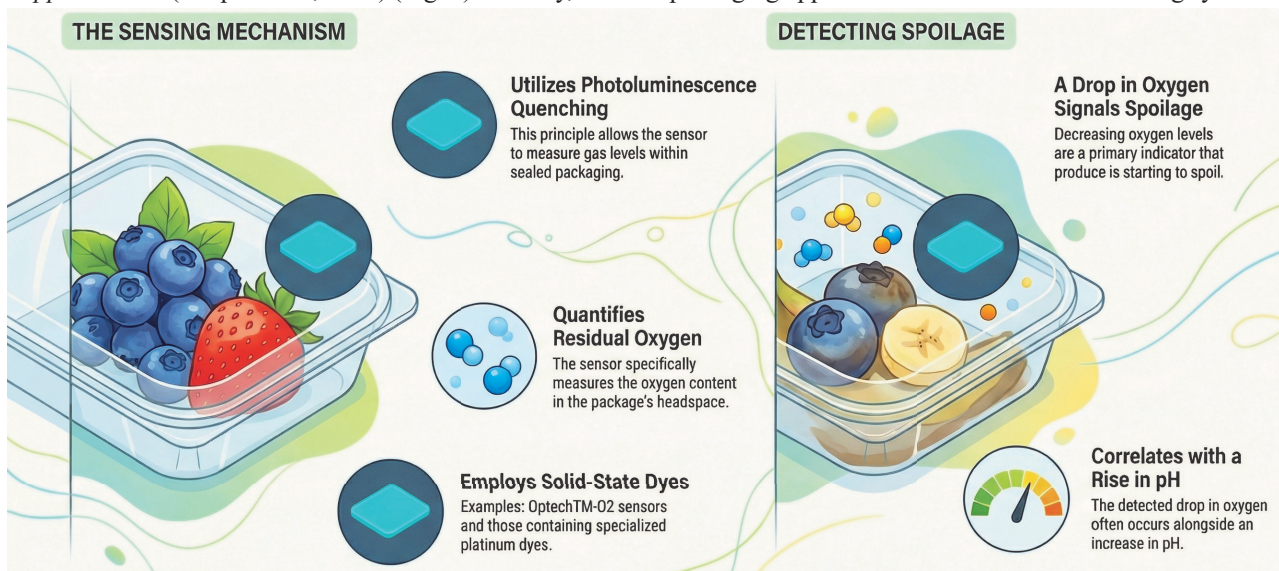


Fig. 8. Schematic diagram of principle function of a biosensor.

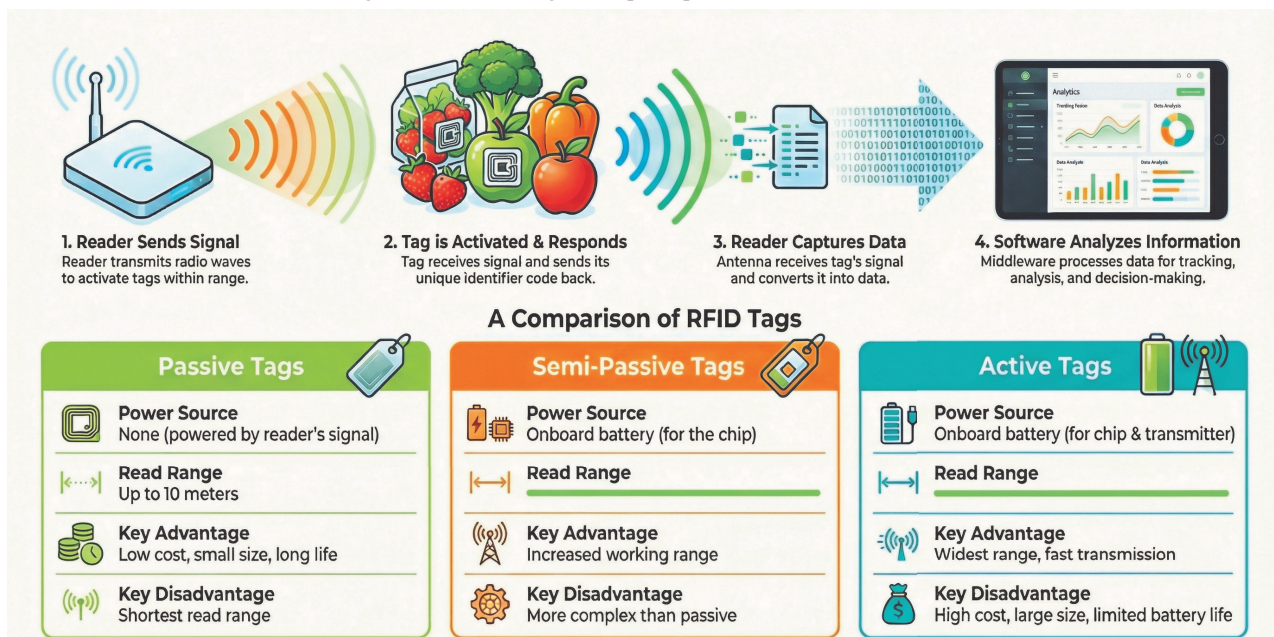


Fig. 9. working mechanism and types of RFID tags.

been developed for the detection of low gas concentrations, with reported sensitivity down to 0.06%. One such sensor incorporates Sudan III as a pH-responsive dye co-immobilized within a sol-gel matrix together with a ruthenium polypyridyl complex. Further optimization of the sensing formulation has been shown to improve selectivity and minimize interference from oxygen during CO<sub>2</sub> measurement (Drago *et al.*, 2020).

**Oxygen sensors:** Oxygen sensing systems used in intelligent packaging are commonly based on mechanisms such as photoluminescence quenching, changes in the lifetime of oxygen-sensitive dyes, and quenching effects within polymeric matrices. Several phosphorescent solid-state oxygen sensors, including Optech<sup>TM</sup>-O<sub>2</sub> and systems incorporating platinum and platinum(II)-benzoporphyrin dyes, have been evaluated for food-packaging applications and demonstrated promising performance following plasma-assisted processing (Pankaj *et al.*, 2016) (Fig. 8). These sensors enable the monitoring of residual oxygen levels in package headspace, providing information on quality deterioration and spoilage in fresh and minimally processed foods. Variations in oxygen concentration, often accompanied by changes in pH, can serve as indicators of ongoing biological and biochemical activity within the packaged product (Morsy *et al.*, 2014). For freshness monitoring, ammonia sensors have attracted considerable interest because ammonia is a common by-product of protein degradation. Matindoust *et al.* (2017) developed a flexible ammonia sensor based on polyaniline, a conductive polymer synthesized through oxidative polymerization. The sensor exhibited high sensitivity together with low energy requirements, highlighting its potential for monitoring quality changes in protein-rich food products.

**Radio frequency identification tags (RFID):** Radio-frequency identification (RFID) technology is widely used in intelligent packaging to facilitate product tracking, identification, and information exchange throughout the supply chain. As an informative and responsive packaging tool, RFID enables wireless data transmission through radio-frequency signals without requiring direct physical contact between the tag and the reader. A typical RFID system comprises three key elements: a tag (transponder), a reader, and supporting software for data processing and management. During operation, the reader emits radio-frequency signals that activate the tag, which subsequently transmits stored information back to the reader. The received signal is then converted into digital data that can be recorded, processed, and utilized for product monitoring and traceability purposes. This data is subsequently processed by the software for analysis and decision-making (Badia-Melis *et al.*, 2015). Each tag contains a circuit with an Electronic Product Code, serving as a unique identifier for tracking purposes. The reader captures the signal and establishes a connection between the tag and the system software. Middleware, which can be either a local network or a web server, manages the entire system (Ghaani *et al.*, 2016). The operational mechanism of the RFID system is illustrated in (Fig. 9).

Three types of RFID tags may be distinguished as active, semi-passive and passive tags. There are no onboard power sources in passive tags. This kind of tag has a typical reading distance up to 10 m depending on the frequency (Tajima, 2007). The interesting properties of the passive tags (low cost, long operational life, small size and lightweight) make them possible candidates for developing low-cost devices. Semi-passive tags are battery-powered to electrically supply the chip only. The tags still rely on

the reader for electromagnetic wave emission. The battery, most of the time, remains inactive and thus increases the life span of the tags. The power source provided on the semi-passive tags increases the working range compared to passive tags (Athauda and Karmakar, 2019). Active tags are embedded with a battery, which is used for powering the chip and for wave emission through an active transmitter. The reading range of the active tags is wider than the passive ones, being of 30 m or more (Tajima, 2007). The transmission rate is fast and the number of tags that can be read simultaneously is high. Multiple writings and readings can be performed on the chips. However, the disadvantages are a high cost and the size of the tag, which is quite invasive. The operational life of the tag depends on the battery life.

Smart packaging has emerged as an important advancement in food packaging by enabling continuous monitoring of product quality, safety, and storage conditions throughout the supply chain. The incorporation of technologies such as time-temperature indicators, freshness indicators, biosensors, gas sensors, and RFID systems has expanded the ability to monitor food products beyond the capabilities of conventional packaging. As discussed in this review, these technologies have shown considerable promise for improving quality management, traceability, and decision-making during storage, transportation, and retail distribution. Despite these advances, broader commercial implementation remains constrained by factors such as production costs, concerns regarding sensor safety, regulatory requirements, and varying levels of consumer acceptance. Addressing these limitations will require further research aimed at developing sustainable, economically viable, and application-specific packaging solutions. Greater regulatory clarity and improved stakeholder awareness may also support wider adoption of these technologies. Overall, smart packaging represents a rapidly evolving area of food packaging research and is expected to play an increasingly important role in meeting future demands for food quality assurance, transparency, and sustainability.

## References

- Abreu, D.A., J.M. Cruz and P. Paseiro Losada, 2012. Active and intelligent packaging for the food industry. *Food Rev. Int.*, 28(2): 146-187.
- Adley, C.C. 2014. Past, present and future of sensors in food production. *Foods*, 3(3): 491-510.
- Alizadeh-Sani, M., E. Mohammadian, J.W. Rhim and S.M. Jafari, 2020. pH-sensitive (halochromic) smart packaging films based on natural food colorants for the monitoring of food quality and safety. *Trends Food Sci. Technol.*, 105: 93-144.
- Almasi, H., S. Forghani and M. Moradi, 2022. Recent advances on intelligent food freshness indicators: an update on natural colorants and methods of preparation. *Food Packag. Shelf Life*, 32: 100839.
- Athauda, T. and N. Karmakar, 2019. Chipped versus chipless RF identification: A comprehensive review. *IEEE Microw. Mag.*, 20(9): 47-57.
- Badia-Melis, R., L. Ruiz-Garcia, J. Garcia-Hierro and J.I.R. Villalba, 2015. Refrigerated fruit storage monitoring combining two different wireless sensing technologies: RFID and WSN. *Sensors*, 15(3): 4781-4795.
- Barska, A. and J. Wyrwa, 2017. Innovations in the Food Packaging Market-Intelligent Packaging- A Review. *Czech J. Food Sci.*, 35(1).
- Becerril, R., C. Nerin and F. Silva, 2021. Bring some color to your package: Freshness indicators based on anthocyanin extracts. *Trends Food Sci. Technol.*, 111: 495-505.
- Chen, S., S. Brahma, J. Mackay and B. Aliakbarian, 2020. The role of smart packaging system in food supply chain. *J. Food Sci.*, 85: 517-525.

- Cierpiszewski, R. 2016. *Opakowania aktywne i inteligentne*. Wydawnictwo Uniwersytet Ekonomiczny w Poznaniu.
- Dobrucka, R. 2013. The future of active and intelligent packaging industry. *LogForum Sci. J. Logist.*, 8: 103–110.
- Dobrucka, R. and R. Cierpiszewski, 2014. Active and intelligent packaging food-Research and development-A review. *Pol. J. Food Nutr. Sci.*, 64: 7–15.
- Drago, E., R. Campardelli, M. Pettinato and P. Perego, 2020. Innovations in smart packaging concepts for food: An extensive review. *foods*, 9(11): 1628.
- Dudnyk, I., E.R. Janecek, J. Vaucher-Joset and F. Stellacci, 2018. Edible sensors for meat and seafood freshness. *Sensors and Actuators B: Chemical*, 259: 1108–1112.
- European Commission. 2009. Commission Regulation (EC) No 450/2009 of 29 May 2009 on active and intelligent materials and articles intended to come into contact with food. *Official Journal of the European Union*, 135: 1–11.
- Fang, Z. Y. Zhao, R.D. Warner and S.K. Johnson, 2017. Active and intelligent packaging in meat industry. *Trends Food Sci. Technol.*, 61: 60–71.
- Gao, T.T., Y. Tian, Z.W. Zhu and D.W. Sun, 2020. Modelling, responses and applications of time-temperature indicators (TTIs) in monitoring fresh food quality. *Trends Food Sci. Technol.*, 99: 311–322.
- Ghaani, M. C.A. Cozzolino, G. Castelli and S. Farris, 2016. An overview of the intelligent packaging technologies in the food sector. *Trends Food Sci. Technol.*, 51: 1–11.
- Ghoshal, G. 2018. Recent trends in active, smart and intelligent packaging for food products. *Food Packaging and Preservation*, 343–374. Academic Press
- Giannoglou, M. A. Touli, E. Platakou, T. Tsironi and P.S. Taoukis, 2014. Predictive modelling and selection of TTI smart labels for monitoring the quality and shelf-life of frozen seafood. *Innov. Food Sci. Emer.*, 26: 294–301.
- Gu, X.L., H.H. Xiao, S.Q. Su, 2002. Time-temperature indicators in cold chain of food. *Food Sci. Technol.*, 12: 43–45.
- Hansen, J.A., J. Wang, A.N. Kawde, Y. Xiang, K.V. Gothelf and G. Collins, 2006. Quantum-dot/aptamer-based ultrasensitive multi-analyte electrochemical biosensor. *J. Am. Chem. Soc.*, 128(7): 2228–9.
- Heising, J.K., M. Dekker, P.V. Bartels and M.A. Van Boekel, 2014. Monitoring the quality of perishable foods: Opportunities for intelligent packaging. *Crit. Rev. Food Sci. Nutr.*, 54: 645–654.
- Kalpana, S., S.R. Priyadarshini, M. Maria Leena, J. A. Moses and C. Anandharamakrishnan, 2019. Intelligent packaging: Trends and applications in food systems. *Trends Food Sci Technol.*, 93: 145–157.
- Kerry, J.P., M.N. O'Grady and S.A. Hogan, 2006. Past, current and potential utilisation of active and intelligent packaging systems for meat and muscle-based products: A review. *Meat Science*, 74: 113–130.
- Kim, D., S. Lee, K. Lee, S. Baek and J. Seo, 2019. Development of a pH indicator composed of high moisture-absorbing materials for real-time monitoring of chicken breast freshness. *Food Sci. Biotechnol.*, 26(1): 37–42.
- Kiryukhin, M.V., H.H. Lau, S.H. Goh, C. Teh, V. Korzh and A. Sadovoy, 2018. A membrane film sensor with encapsulated fluorescent dyes towards express freshness monitoring of packaged food. *Talanta*, 182: 187–192.
- Lv, C.X., B.X. Sun and X.Q. Feng, 2012. Application of time-temperature indicators as quality monitors in food packaging. *J. Food Nutr. Sci.*, 1(2): 5–9.
- Mahalik, N.P. and A.N. Nambiar, 2010. Trends in food packaging and manufacturing systems and technology. *Trends Food Sci. Technol.*, 21(3): 117–128.
- Matindoust, S., A. Farzi, M. Baghaei Nejad, M.H. Shahrokh Abadi, Z. Zou and L.R. Zheng, 2017. Ammonia gas sensor based on flexible polyaniline films for rapid detection of spoilage in protein-rich foods. *J. Mater. Sci. Mater. Electron.*, 28(11): 7760–7768.
- Mohammadi, Z. and S.M. Jafari, 2020. Detection of food spoilage and adulteration by novel nanomaterial-based sensors. *Adv. Colloid Interface Sci.*, 286: 102297.
- Morsy, M.K., H.H. Khalaf, A.M. Sharoba and H.H. El-Tanahi, 2014, April. Applicability of biosensor and oxygen sensor for monitoring spoilage and bacterial contaminants of packed minced beef and poultry. In: *Proceedings of the 2nd International Conference on Biotechnology Applications in Agriculture (ICBAA), Hurghada, Egypt*. pp. 8–12.
- Muller, P. and M. Schmid, 2019. Intelligent packaging in the food sector: a brief overview. *Foods*, 8(1): 16.
- Navrotskaya, A. Aleksandrova, D. Chekini, M. Yakavets, I.S. Kheiri and E. Krivoschapkina, 2022. Nanostructured temperature indicator for cold chain logistics. *ACS Nano*, 16: 8641–8650.
- Nopwinyuwong, A., S. Trevanich and P. Suppakul, 2010. Development of a novel colorimetric indicator label for monitoring freshness of intermediate-moisture dessert spoilage. *Talanta*, 81: 1126–1132.
- Nowacka, M. and A. Fijalkowska, 2014. Application of intelligent packaging in the fermentation and fruit and vegetable industry. *Fermentation and Fruit and Vegetable Industry*, 58: 06–12.
- Pal, M., M. Devrani and A. Hadush, 2019. Recent developments in food packaging technologies. *Food and Beverage World*, 46(1): 21–25.
- Pankaj, S.K., C.A. Kelly, C. Bueno-Ferrer, J.P. Kerry, D.B. Papkovsky and P. Bourke, 2016. Application of phosphorescent oxygen sensors in in-package dielectric barrier discharge plasma environment. *Innov. Food Sci. Emerg. Technol.*, 33: 234–239.
- Pavelkova, A. 2013. Time temperature indicators as devices for intelligent packaging. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, 61(1): 245–251.
- Pereira, V.A., I.N.Q. de Arruda and R. Stefani, 2015. Active chitosan/PVA films with anthocyanins from *Brassica oleraceae* (Red Cabbage) as Time-Temperature Indicators for application in intelligent food packaging. *Food Hydrocolloids*, 43: 180–188.
- Schaude, C., C. Meindl, E. Frohlich, J. Attard and G.J. Mohr, 2017. Developing a sensor layer for the optical detection of amines during food spoilage. *Talanta*, 170: 481–487.
- Singh, S., K.K. Gaikwad, M. Lee and Y.S. Lee, 2018. Temperature-sensitive smart packaging for monitoring the shelf life of fresh beef. *J. Food Eng.*, 234: 41–49.
- Sohail, M. D.W. Sun and Z. Zhu, 2018. Recent developments in intelligent packaging for enhancing food quality and safety. *Crit. Rev. Food Sci. Nutr.*, 58(15):2650–2662.
- Su, L., W. Jia, C. Hou and Y. Lei, 2011. Microbial biosensors: A review. *Biosensors & Bioelectronics*, 26(5): 1788–99.
- Tajima, M. 2007. Strategic value of RFID in supply chain management. *Journal of Purchasing and Supply Management*, 13: 261–273.
- Thapar, P., M.K. Salooja and R.K. Malik 2017. Application of biosensors for detection of contaminants in milk and milk products. *Acta Scientific Microbiology*. 1(12):17-24.
- Wang, M. Li. Y., P. Srinivasan, Z. Hu, R. Wang and A. Saragih, 2018. Interactions between biological products and product packaging and potential approaches to overcome them. *AAPS Pharm. Sci. Tech.*, 19(8): 3681–3686.
- Wang, S., X. Liu, M. Yang, Y. Zhang, K. Xiang, and R. Tang, 2015. Review of time-temperature indicators as quality monitors in food packaging. *Packaging Technology and Science*, 28(10): 839–886.
- Wang, W., J.M. Zhang and Y. Zhang, 2003. A novel photochromic time-temperature indicator to support cold chain management. *Food. Ferment. Technol.*, 49(2): 89–93.
- Yam, K.L., P.T. Takhistov and J. Miltz, 2005. Concise reviews/hypotheses in food science intelligent Packaging: package devices. *J. Food Sci.*, 70(1): 1–10.
- Yam, K.L. and D.S. Lee, 2012. Emerging food packaging technologies: An overview. In *Emerging Food Packaging Technologies*; Woodhead Publishing Series in Food Science, Technology and Nutrition, 1–9.
- Yousefi, H., H.M. Su, S.M. Imani, K. Alkhalidi, C.D. Filipe and T.F. Didar, 2019. Intelligent Food Packaging: A Review of Smart Sensing Technologies for Monitoring Food Quality. *ACS Sens.*, 4: 808–821.
- Zhai, X., X. Zou, J. Shi, X. Huang, Z. Sun, Z. Li and J. Xiao, 2020. Amine-responsive bilayer films with improved illumination stability and electrochemical writing property for visual monitoring of meat spoilage. *Sensors and Actuators B: Chemical*, 302: 127–130.

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