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Supriya M Kamble
Research Scholar, Department
of Food Technology, Institute
of Bioscience and Technology,
MGM University, Chhatrapati
Sambhajanagar, Maharashtra,
India

Manmath Sontakke
Assistant Professor,
Department of Food
Technology, Institute of
Bioscience and Technology,
MGM University, Chhatrapati
Sambhajanagar, Maharashtra,
India

Raut Vishal P
Research Scholar, Department
of Food Technology, Institute
of Bioscience and Technology,
MGM University, Chhatrapati
Sambhajanagar, Maharashtra,
India

Corresponding Author:
Supriya M Kamble
Research Scholar, Department
of Food Technology, Institute
of Bioscience and Technology,
MGM University, Chhatrapati
Sambhajanagar, Maharashtra,
India

Advancements in intelligent packaging: Enhancing safety, quality, and traceability in muscle food

Supriya M Kamble, Manmath Sontakke and Raut Vishal P

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Abstract

The food packaging industry has seen significant advancements with the integration of intelligent, active, and smart packaging technologies. These innovations aim to enhance food safety, quality, and traceability throughout the supply chain mainly in muscles food. Intelligent packaging systems, including gas sensors, biosensors, Nano sensors, and data carriers like RFID and QR codes, have been developed to monitor various factors such as microbial contamination, spoilage, temperature changes, and freshness. These systems leverage sensors that detect chemical and physical changes in food products, providing real-time data to both consumers and manufacturers. Gas sensors, for instance, monitor gases like CO₂ and O₂ to detect food spoilage, while biosensors enable the detection of pathogens and contaminants. Nano sensors have advanced food safety through their high sensitivity to changes in the environment, such as humidity and temperature, and by detecting harmful chemicals or pathogens. Data carriers like RFID and QR codes facilitate food traceability, inventory management, and transparency, allowing consumers to easily access product information. Despite the promising applications of these technologies, challenges remain in commercializing and optimizing them for widespread use. This paper reviews the key components, applications, and benefits of these advanced packaging systems and highlights the potential for further development to improve food safety and sustainability in muscle food industry.

Keywords: Intelligent packaging, active packaging, traceability, gas sensors, biosensors, nano sensors, RFID, QR codes

Introduction

Every time we throw away food, we're not just wasting a meal—we're wasting the effort of the farmer, the energy used in processing, the resources spent on transportation, and the opportunity to feed someone in need. Recent estimates reveal that nearly 30% of all food produced is lost somewhere between the farm and our plates (Parfitt *et al.*, 2010) ^[107]. In a country like India, known for its rich culinary heritage and diverse food culture, this loss hits especially hard.

Despite being a land of abundant flavors, India faces a heartbreaking contradiction: around 23 crore people still go hungry, while an estimated ₹50,000 crore worth of food goes to waste each year, according to the Ministry of Agriculture. The FSSAI has also reported that nearly one-third of all food produced in the country is wasted before it ever reaches a plate (Nath, 2021) ^[96]. This isn't just about carelessness—it's a systemic issue involving poor handling, inefficient transportation, inadequate storage, and a widespread lack of awareness. The tragedy of food wastage in India isn't just a matter of lost meals—it's about lost potential, especially when millions still sleep hungry each night (Awlqadr *et al.*, 2024) ^[4]. A significant amount of food goes bad simply because of preventable issues during storage, transport, or even at home.

In light of this, researchers and technologists are stepping up, working on innovative solutions like smart food sensors. These small but powerful devices can detect the freshness, quality, and even contamination of food—and then communicate that information to consumers. One area that shows great promise is the use of these sensors within food packaging. Proper packaging doesn't just keep food clean—it protects it from damage, extends shelf life, and ensures quality throughout the supply chain (Cribb, 2010) ^[23].

But here's the puzzle: despite the urgent need and the availability of technology, these food sensors haven't yet become mainstream. Why? That's a question researchers are trying to

answer. Colourimetric, optical, and electrical sensors, in particular, offer fast, affordable, and reliable ways to monitor food-and they're perfect for integration into packaging systems (Ha, 2025) ^[46].

This review focuses on the application and future potential of colourimetric, optical, and nanosensors in ensuring food quality and safety across different food types. With more people demanding transparency and safety in what they eat, traditional methods of food analysis-though accurate-are often slow and tedious. The modern food system is complex, involving everyone from producers and transporters to retailers and consumers, all of whom are asking for better packaging that gives real-time updates about food quality.

This is where intelligent packaging comes in. This new approach to packaging doesn't just protect food-it communicates with the user, offering updates on freshness, tracking its journey from farm to table, and even alerting when something has gone wrong (Xiaoxuan *et al.*, 2023). In some systems, the packaging itself can record and show key information like manufacture date, storage conditions, and expiration. Some advanced labels even change color or display words like "STOP" or "OPENED" when tampered with (Bagchi, 2012; Vanderroost *et al.*, 2014) ^[7].

These innovations are not science fiction-they are real, tangible advancements being tested and improved every day. Intelligent packaging systems, powered by embedded sensors, offer a promising way to extend shelf life, reduce waste, ensure safety, and ultimately, make food more accessible and secure for all (Realini & Marcos, 2014) ^[118].

Based on the information provided above, modern consumers' demands are constantly changing to include more natural bioactive ingredients with beneficial health effects and new muscle food items with minimal amounts of artificial additives. Meat, poultry, and fish products are examples of muscle foods that are high in nutrients including protein, fat, and minerals. (McWilliams, 2012; Keeton, 2017) ^[86]. However, post-mortem changes that result in the production of spoiling substances including

organic acids, aldehydes and ketones, alcohols, sulphides, and biogenic amines make them extremely perishable (Kuley *et al.*, 2017) ^[62]. Muscle product quality identification has always depended on sensory assessment and physicochemical index evaluation. The decline of muscle foods' flavour, colour, texture, and nutritional content during processing or storage affects how acceptable they are. (Lorenzo *et al.*, 2014, Falowo, 2014) ^[79, 35] of these indices, one of the most significant elements influencing consumers' purchasing decisions is the muscle food's odor quality. For decades, sensors have been created to detect the quality of muscle foods in a fast, accurate, easy-to-use, and even online manner. This review's primary goals are to offer some perspectives on the sensors already in use for muscle meals and to make recommendations for potential directions for future research.

Intelligent packaging technology

Intelligent packaging is an emerging technology that's transforming the food packaging industry. These systems are designed to sense and share information about changes in the environment inside or outside the package. They hold great promise for improving food safety, traceability, and real-time quality monitoring. One of the key factors that influences consumer choices-especially when it comes to muscle foods like meat and fish-is odor quality. For many years, gas sensors have been developed to quickly and accurately detect changes in odor, helping ensure freshness and prevent spoilage.

This review focuses on current gas sensor technologies used in monitoring the quality of muscle foods and explores how this field can evolve in the future. Generally, intelligent packaging systems operate in two main ways. The first type uses sensors or indicators embedded in the packaging to monitor environmental conditions such as temperature, gas composition, or microbial activity. The second type includes data carriers like barcodes and RFID (radio-frequency identification) tags that store and transmit information throughout the supply chain (Bagchi *et al.*, 2012) ^[7].

Sensor	Indicators	Data carriers
• Gas sensor • Chemical sensor • Biosensor • Nanosensors	• Time-Temperature Indicators • Freshness indicators • pH indicators	• RFID tags • Bar codes • QR code

Sensor

Gas Sensors: When food begins to spoil due to microbial activity, it often releases gases that cause unpleasant odors. These gases serve as early warning signs of spoilage, and scientists have developed special sensors that can detect them. Inspired by how our nose works, these sensors are added to food packaging to monitor gas levels and help determine the freshness of the food inside.

Some of the key gases that are monitored include carbon dioxide (CO₂), oxygen (O₂), volatile organic compounds (VOCs), and biogenic amines (BAs). Usually, a small sticker-like label is placed on the packaging that changes color when these gases are detected, especially CO₂, O₂, or ethylene (C₂H₄), indicating whether the food is still fresh (Jong *et al.*, 2005) ^[27].

Spoilage in muscle-based foods like meat and fish can lead to bad flavors. For example, in fish, a compound called

trimethylamine oxide (TMAO) breaks down into trimethylamine (TMA) and dimethylamine (DMA), both of which have strong, fishy odors. These chemicals are often used as freshness indicators (Messenger *et al.*, 2013; Wu *et al.*, 2019; Niizeki *et al.*, 2002) ^[88, 153, 97]. Another common measurement is TVB-N (Total Volatile Basic Nitrogen), a standard test used worldwide to check how spoiled fish is. However, this traditional test takes time and needs careful handling.

To make this process faster, researchers like Mani *et al.* (2015) ^[83] have developed special sensors using nanotechnology. They created metal oxide sensors, using materials like cobalt-doped zinc oxide (ZnO), to quickly detect ammonia gas - another sign of spoilage.

Similarly, Chang *et al.* (2017) ^[16] developed a new type of organic gas sensor using a material called P3HT, which responds to gases by changing its electrical properties.

Detecting food fraud is also critical. A famous example is the 2013 European horse meat scandal, where cheaper horse meat was sold as beef. This incident highlighted the need for fast and reliable methods to detect adulteration (Tian *et al.*, 2019) [137].

Some advanced packaging technologies now include smart films that react to changes in gas levels inside the package. For instance, CO₂-sensitive films can change color when CO₂ builds up, giving a clear visual cue about the food's freshness (Baek *et al.*, 2018; Lee *et al.*, 2019; Lyu *et al.*, 2019) [6].

These smart indicators can track gases like CO₂, ammonia (NH₃), hydrogen sulfide (H₂S), DMA, and TMA. Although they are very helpful, not many research studies have been published on their use for everyday food quality monitoring. One simple and effective method is the use of color-changing indicators based on redox reactions. These often use compounds like sodium or potassium hydroxide. To detect oxygen, which also plays a role in spoilage, a combination of methylene blue and a reducing agent like glucose is used (Putr *et al.*, 2022; Won *et al.*, 2021) [111, 152]. There are also many types of gas sensors available, including:

- Oxygen sensors (amperometric)
- CO₂ sensors (potentiometric)
- Metal oxide sensors
- Piezoelectric sensors

- Sensors made from conductive organic materials (Müller *et al.*, 2019; Chowdhury *et al.*, 2019) [93, 21].

Interestingly, CO₂ can pass more easily through packaging materials than oxygen. Because of this, it can get absorbed into the food, which may change the pressure inside the package and cause it to deform. To manage this, carbon dioxide regulators are sometimes used to maintain the right levels and prevent package damage (Han *et al.*, 2018) [48].

Other advanced devices use infrared, ultrasonic, laser, or electrochemical systems to detect gas changes and help keep food safe and fresh (Pandey *et al.*, 2007; Park *et al.*, 2015) [105, 108].

1.2 Biosensors

The biological sensor was defined by Fracchiolla *et al.* (2013) [37] as follow: "Biosensors are devices that are capable of detecting specific biological analyses and converting their presence or concentration into some electrical, thermal, optical or other signals that can be easily analyzed". Biosensor sensor in which a biological analyte plays the role of detection of a change, further converted into an electric signal using a transducer, is a biosensor. Biosensors generally are made up of mainly two components, firstly bioreceptors and secondly a transducer (Müller *et al.*, 2019) [93].

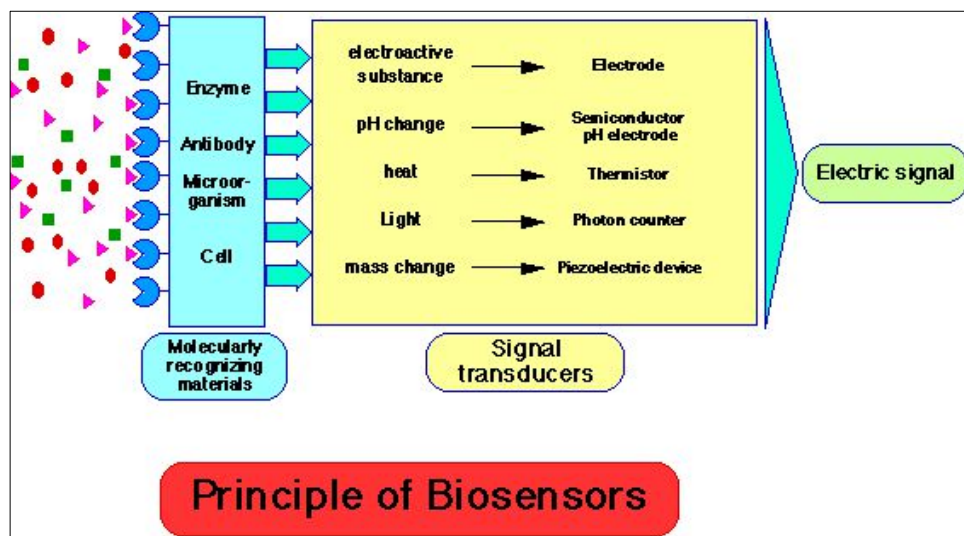


Fig 1: Principle of Biosensors

Biosensors come in many types, each working in a unique way to detect and analyze different substances. Depending on how they function, biosensors can be grouped into several categories: electrochemical biosensors (Hansen *et al.*, 2006) [49], optical biosensors (Haes & Van Duyne, 2002) [47], immobilized biosensors (Sassolas *et al.*, 2012) [123], piezoelectric sensors (Zhou *et al.*, 2002), microbial biosensors (Su *et al.*, 2011) [134], and those based on nanomaterials.

For example, one innovative biosensor was designed specifically to monitor the freshness of protein-rich foods like beef and chicken. This sensor detects spoilage by changing color-from green (fresh) to red-after 9 days for beef and 10 days for chicken, effectively showing the product's spoilage history (Fang *et al.*, 2017) [36].

The basic working principle of a biosensor starts with the bioreceptor, which detects the specific substance (analyte). Then, a transducer converts this biological interaction into an electrical signal. This signal is often very weak, so an amplifier boosts it, maintaining the original pattern. Finally, the signal processor interprets the signal and displays it for analysis or recording.

Among all types, electrochemical biosensors are especially promising for food packaging because they continuously monitor food quality and provide signals directly related to the concentration of a substance (Park *et al.*, 2015) [108]. Many of these biosensors use enzymes, which makes them simple, cost-effective, compact, and easy to integrate into packaging without needing extra equipment. Enzymes are naturally selective and specific to certain molecules, so

there's often no need to prepare or separate food samples beforehand (Ronkainen *et al.*, 2010) ^[121].

However, most biosensors only show the current freshness status—they can't provide a full history of quality over time (Park *et al.*, 2015) ^[108].

In recent years, biosensors have also been developed to detect food contaminants like pathogens and toxins (Gaudin, 2019; Sabet *et al.*, 2017; Singh *et al.*, 2013; Younis *et al.*, 2020) ^[40, 131, 162]. These sensors can directly measure spoilage-related compounds inside sealed packaging—without the need to open or process the food sample.

Some of the most successful applications involve detecting volatile compounds like ethylene (Esser *et al.*, 2012; Weber *et al.*, 2009) ^[32, 148], alcohols (Bekmezci *et al.*, 2020; Schlangen *et al.*, 2012) ^[8, 125], and amines (Verma *et al.*, 2020) ^[142], which often signal food spoilage.

A research group led by Tai Hyun Park has developed biosensors that use olfactory receptors—similar to those in the human nose—to identify specific smells. These sensors can detect even tiny amounts of odor compounds such as amyl butyrate (Kim *et al.*, 2009; Jin, 2012) ^[61, 55], octanal (Lee, 2009; Yang, 2017) ^[69, 158], geraniol and citronellol (Lee, 2018) ^[68], bourgeonal, β -citronellol (Lee, 2015) ^[70, 71], and cadaverine. Although many of these biosensors show great potential, they are still in the design and testing stages. More development is needed to make them commercially ready and compliant with safety and regulatory standards (Mustafa & Andreescu, 2018) ^[94].

Nanosensors

Nanosensors are advanced tools developed using bio-nanocomposite polymer materials, strengthened with tiny particles known as nanofillers. These fillers can include substances like silica nanoparticles (SiO₂), clay nanoplatelets, starch nanocrystals, carbon nanotubes, graphene, chitin or chitosan nanoparticles, cellulose nanofibers, and various metal oxides (such as silver, copper, zinc oxide, and titanium dioxide) (Ranjan *et al.*, 2016) ^[116]. The primary aim of these nanosensors is to detect and measure harmful chemicals—such as allergens, pesticides, toxins (both chemical and microbial), and spoilage by-products—as well as environmental changes like humidity, temperature, and gas levels (Kim *et al.*, 2013) ^[60].

Just like regular sensors, nanosensors consist of two main parts: a receptor and a transducer. The receptor interacts specifically with the target substance (called the analyte), while the transducer converts this interaction into a measurable signal, which could be electrical, electrochemical, or optical.

In the dairy industry, nanosensors are used to detect harmful microorganisms with impressive accuracy. For instance,

they help identify *Mycobacterium avium* subsp. *paratuberculosis* using surface-enhanced Raman scattering, detect *Brucella abortus* antibodies in milk via fluorescent silica nanoprobe, and sense *Escherichia coli* O157:H7 using gold nanoparticles applied to special carbon electrodes (Yakes *et al.*, 2008; Vyas *et al.*, 2015; Lin *et al.*, 2008) ^[155, 144, 75]. More broadly, these nanosensors are incorporated into food packaging systems to continuously monitor the internal and external conditions surrounding the food (Ramachandiraiah *et al.*, 2015) ^[115]. A key goal, especially from a microbiological perspective, is to drastically cut down the time it takes to detect pathogens—from several days to just hours or even minutes.

Researchers have explored various applications of nanosensors in food safety. For example:

- They can detect gases and molecules using surface-enhanced Raman spectroscopy (Duncan *et al.*, 2011) ^[30].
- In raw meat packaging, nanosensors help detect oxygen levels.
- “Electronic tongues” made from arrays of nanosensors can pick up gases released from spoiled food, offering clear visual cues about freshness.
- Fluorescent nanoparticles can identify pathogens and toxins in food and crops (Burris *et al.*, 2012) ^[14]. These include bacteria like *Salmonella typhimurium*, *Shigella flexneri*, and *E. coli* O157:H7 in foods such as milk and juice (Zhao *et al.*, 2009) ^[168].
- Some nanosensors are designed to detect temperature or humidity changes that could signal spoilage (Iliadis *et al.*, 2011; Lee *et al.*, 2011; Zhang *et al.*, 2008) ^[52, 66].
- Food companies like Kraft are even exploring nanosensors that can assess consumer preferences, allergies, and nutritional deficiencies (Meetoo, 2011) ^[87].
- Detection of pesticide residues like organophosphates is also possible (Liu *et al.*, 2008).

In another innovative approach, nanowires coated with fluorescent antibodies can detect harmful bacteria. For instance, when *Salmonella* bacteria are present in a food sample, the fluorescent signal changes upon binding, providing a clear and quick detection method (Dingman, 2008) ^[28].

Lastly, even natural materials are being used in nanosensor technology. For example, silver nanoparticles derived from tea leaf extract have shown strong antibacterial activity, and they are now being used in packaging meat products to prevent contamination from harmful Gram-negative bacteria (Loo *et al.*, 2018) ^[78].

Table 1: Food products, Packaging system, Mode of action

Sr. No	Food products	Packaging system	Mode of action	References
1	Red meat	Biosensor	Optical detection of amines	Schaude <i>et al.</i> (2017) ^[124]
	Minced beef		Alizarin colourimetric indicator	Ezati <i>et al.</i> (2019) ^[34]
2	Meat	Nano sensor	Zinc oxide nanoparticles: Highly applicable in case of biosensing (<i>Aspergillus terreus</i>)in food packaging	Raliya <i>et al.</i> (2014) ^[114]
	Beef		Silver nanoparticles for Beefpreservation	Wasiu Oluwatofarati <i>et al.</i> (2018) ^[147]
	Fish		Goldandsilver nanoparticles Act as excellent sensors agents with potential use in food packaging	Mondal <i>et al.</i> (2011) ^[91]
3	Meat, Fish	Gas Indicator	Gas detection	(Abraham <i>et al.</i> 2022) ^[2]
			CO2, NH3, H2S and dimethylamine ((CH3)2NH) and trimethylamine (C3H9N) gas detection	Messenger <i>et al.</i> (2013) ^[88]
4	Meat, Fish	optical biosensors	Biological molecules or reactions	(Haes and Van Duvne, 2002) ^[47]

Indicators

Time-Temperature Indicators

Temperature indicators play a crucial role in ensuring food safety by continuously monitoring the temperature of products, especially perishable items. These indicators are sensitive to environmental temperature changes and can detect even brief deviations from the safe storage range. Since temperature greatly influences the rate at which food spoils, especially in perishable items, maintaining proper temperature throughout the food cold chain is essential. During processes like transportation, loading, and unloading, temperature fluctuations are common and can significantly affect the shelf life and quality of food products.

One of the most effective tools in monitoring such conditions is the Time-Temperature Indicator (TTI). TTIs are designed to track the temperature history of a product and signal whether it has been exposed to unsafe temperature conditions for a critical period. They function by monitoring temperature-dependent changes, such as chemical reactions or physical processes like diffusion.

TTIs offer a visible indication—often through a change in color—of the cumulative temperature exposure during distribution and storage. This makes them especially useful for frozen and chilled foods. A noticeable color shift on the packaging or indicator surface alerts handlers and consumers if the food has been compromised due to temperature abuse.

There are several types of TTIs, categorized based on their working principles: chemical, physical, enzymatic, and biological systems.

Chemical TTIs change color due to specific chemical reactions, including polymerization, photochromic transitions, or oxidation reactions (Girardeau *et al.*, 2020).

For instance, Wanihsuksombat, Hongtrakul, and Suppakul

(2010)^[146] developed a chemical-based TTI using a mixture of bromothymol blue and methyl red, which shifted from bright green to red when exposed to increasing levels of lactic acid vapors. This approach proved effective in tracking food quality over time.

Mixing multiple dyes has also shown to enhance the range and clarity of color change compared to using single indicators alone (Lim *et al.*, 2014)^[74].

TTIs based on microbial activity have also been explored. Lim *et al.* (2014)^[74] developed a microbial TTI using *Weissella koreensis* that could track spoilage by mimicking the temperature sensitivity of certain food products. This microbial system proved useful for monitoring food quality when the activation energy (E_a) of the TTI closely matched that of the food being monitored.

Giannoglou *et al.* (2019)^[41] tested enzymatic TTIs on smoked seafood products like European eel, rainbow trout, and salmon. These TTIs worked by enzyme-driven hydrolysis, resulting in a gradual drop in pH and a corresponding color shift from green to red. Quality control was ensured by measuring lipase activity using a spectrophotometric method with *p*-nitrophenyl as a substrate.

In another study, Hsiao and Chang (2017)^[50] designed a microbial TTI for vacuum-packed giant grouper fish fillets (*Epinephelus lanceolatus*), using *Lactobacillus sakei*, a common spoilage bacterium, to simulate realistic spoilage conditions.

One key advantage of TTIs is their ease of interpretation by consumers and handlers. A simple color change provides an immediate visual cue about the freshness or potential spoilage of a product. By tailoring these indicators to specific food products and temperature sensitivities, TTIs help strengthen quality control throughout the cold chain, thereby enhancing food safety and reducing waste.

Table 2: Intelligent Packaging system, Mode of action, Area of application

Intelligent Packaging system	Mode of action	Area of application	Reference
Time temperature indicators; 1. Enzymatic TTI 2. Diffusion-based TTI 3. Microbial TTI	Enzymatic reactions Rate of diffusion of a substance Microbial activity Antimicrobial	Beef products Quail eggs Poultry, Egg Pork	(Jhuang <i>et al.</i> , 2020) ^[53] (Shari <i>et al.</i> , 2020) ^[129] (Yang <i>et al.</i> , 2019) ^[159] Morelli <i>et al.</i> (2012) ^[192]
Freshness Indicators	Biochemical reactions The starch-based film incorporated with anthocyanins of butterfly pea flower and TiO ₂ is used as a pH indicator to monitor the freshness of the prawn	Meat, fish Prawn	Wyrwa <i>et al.</i> , 2017 ^[154] Mary <i>et al.</i> (2020) ^[85]
	Tyvek® sheet and RGB colour analysis Solid polymer substrates and coated fibres containing 2,4,6-trinitrobenzene motifs	Chicken breast Tuna and beef	Lee <i>et al.</i> (2019) Pablos <i>et al.</i> (2015) ^[103]
Leak indicators	Changes in gas concentration	Fish, Dairy, fruits	Jurica <i>et al.</i> , 2021 ^[56]
pH indicator	Changes in acidity or alkalinity	Pork fish meat	(Zhang X, <i>et al.</i> 2014) ^[166]
	The development of pH-sensitive packaging films using cassava starch and <i>L. ruthenicum</i> anthocyanins to monitor the freshness of pork.	Pork	Qin <i>et al.</i> (2019) ^[112]
Gas Indicator	Gas detection	Dairy, meat, Fish	(Abraham <i>et al.</i> , 2022) ^[2]
Radio-frequency identification tags	Freshness monitoring	Meat Pork Meat Chilled meat	Eom <i>et al.</i> (2014) ^[31] Sen <i>et al.</i> (2013) ^[126] Townsend and Mennecke (2008) ^[139] Swedberg (2011) ^[135]
		All food	(Vu <i>et al.</i> , 2013) ^[143]
Bar code, QR code	Tracking of food		

2.2 Freshness indicators: Freshness indicators are special tools placed inside food packages that help us understand whether the food inside is still good to eat. They work by changing color based on what's happening inside the package—like detecting spoilage, harmful microbes, or chemical changes in the food. Because they offer a simple

visual signal, they are becoming increasingly popular with food companies, retailers, and safety regulators. Everyone wants methods that are fast, reliable, low-cost, and non-destructive to ensure food is fresh in real-time.

One of the main reasons food loses its freshness is due to poor storage conditions or microbial contamination.

Microorganisms not only reduce the shelf life of food but also increase the risk of foodborne illnesses. During spoilage, foods can release gases like carbon dioxide and amines or produce byproducts like acids. All these internal activities can be detected using freshness indicators placed in direct contact with the food.

For example, in fish products, an increase in total volatile basic nitrogen (TVB-N) indicates spoilage. Similarly, in meats, the presence of compounds like lactic acid, acetic acid, or n-butyrate signals microbial activity and loss of freshness. These indicators often rely on color-changing dyes that respond to pH changes. Natural dyes from sources like turmeric (curcumin), grape peel, and beetroot have been tested successfully in this role. For example, a sensor using bromocresol purple embedded in an absorbent pad can detect spoilage in chicken breasts by monitoring pH changes.

Advanced systems combine different dyes (like methyl red and bromocresol purple) to create dual sensors for beef freshness. These color changes provide a visual cue that is easy for consumers and sellers to interpret (Kim *et al.*, 2017; Kuswandi & Nurfawaidi, 2017) ^[64].

Leak Indicators: Ensuring Packaging Integrity

Leak indicators help detect if the packaging has been compromised. This is especially important in Modified Atmosphere Packaging (MAP), where the gases inside the package are carefully controlled to extend shelf life. Any leak can disturb the gas balance, affecting the food's taste, safety, and texture.

Some packaging solutions use materials sensitive to moisture, pressure, or gas levels. For instance, in vacuum packaging, an air pressure indicator can detect CO₂ buildup due to leaks using a pH-sensitive dye like o-cresolphthalein. This dye changes color based on gas concentration and is embedded in a simple ethyl cellulose solution (Yusufu *et al.*, 2019) ^[164]. Innovations have also led to UV-activated oxygen indicators. These use a redox dye (like methylene blue), a photocatalyst (such as TiO₂), and a sacrificial electron donor to respond to oxygen exposure. The indicator can be printed on packaging films using inkjet printers-making it low-cost and scalable (Vu & Won, 2013; Lawrie *et al.*, 2005; Khankaew *et al.*) ^[143, 65].

pH Indicators: A Window into Chemical Changes

pH indicators help track freshness by detecting acidity or alkalinity changes inside the food packaging-often caused by microbial spoilage. These indicators are commonly made from natural sources like anthocyanins (from berries, red cabbage, etc.), litmus, and curcumin.

As microbes grow, they break down proteins and release acids or amines, altering the pH. This change is picked up by color-sensitive films placed inside the package. These films are made from biodegradable materials like chitosan (from crab or shrimp shells) or cellulose, combined with pH-sensitive dyes.

These pH-sensitive systems are versatile-they can work as liquid indicators, gas sensors, or even be combined into hydrogels. One such hydrogel-based passive pH sensor can help detect volatile spoilage compounds like amines (Bhadra *et al.*, 2015) ^[10].

Such materials not only monitor freshness effectively but are also environmentally friendly, biodegradable, and

suitable for sustainable packaging (Liu *et al.*, 2020; Patricia *et al.*, 2019) ^[77, 109].

Data Carriers: Smart Packaging for the Digital Age

Data carrier devices like barcodes and RFID tags help track and manage food items throughout the supply chain. They carry important product information like origin, batch number, expiry date, and even real-time freshness data. These devices support inventory control, reduce labor, prevent theft, and help trace back any safety issues.

Barcodes are the most common and economical form of data carriers. They come in two types:

- 1D barcodes (the familiar vertical black bars),
- 2D barcodes (like QR codes) which store more information.

New ideas are exploring combining QR codes with color-changing dyes to also reflect freshness. Some researchers have tried encoding these in geometric shapes using micro-beads and attaching them to tape or filter paper to act as both data carriers and freshness indicators.

Though these technologies are promising, their adoption may face challenges due to user complexity, especially among consumers not familiar with mobile apps or scanning tools.

Radiofrequency identification (RFID)

RFID Tags: Smart Technology in Food Packaging

Radio Frequency Identification (RFID) tags represent a smart, wireless technology that uses radio waves to identify and track products. Each RFID tag carries a unique identification code and essential information, which a reader can access by receiving radio signals. This data is then processed by a computer to provide real-time updates—such as temperature, humidity levels, nutritional facts, or even cooking instructions-to users.

Typically, low-frequency (125-134 kHz) and high-frequency (13.56 MHz) RFID systems are used in food packaging (Bibi *et al.*, 2017). The tag's antenna acts as a bridge for electromagnetic waves, helping transmit information between the tag and the reader (Chen *et al.*, 2008) ^[19].

RFID has already found widespread use across the food industry, including for horticultural products, meat, seafood, dairy, bakery items, and beverages (Costa *et al.*, 2013) ^[22]. In the case of seafood, for instance, RFID tags can be printed onto smart labels that help detect spoilage by monitoring humidity levels and volatile amines-key indicators of freshness. These smart tags can even track changes in temperature and humidity throughout cold chain logistics, ensuring fish remain fresh until they reach consumers (Abad *et al.*, 2009) ^[1].

Recent developments show how RFID is evolving further. Shafiq *et al.* (2019) ^[127] introduced a passive RFID temperature sensor capable of tracking the cold chain for perishable foods or pharmaceuticals-providing a cost-effective monitoring solution. Lorite *et al.* (2017) ^[80] designed a critical temperature sensor that uses a phase-change solvent and color change to enable real-time food monitoring. Trebar *et al.* (2015) ^[140] highlighted how combining RFID and temperature sensors can help monitor logistics conditions for sea bass, optimizing freshness and safety.

Other innovations include using infrared spectrometry with moisture sensors to analyze the packaging environment and chipless RFID-based humidity sensors that provide real-time tracking of moisture levels (Nair *et al.*, 2012) ^[95]. These advances not only enhance food safety but also support sustainable packaging solutions.

Quick Response (QR) Codes

Quick Response (QR) codes, which look like patterns of squares or dots, are widely used on all levels of packaging—primary, secondary, and tertiary. Like barcodes, they store data, but in a much more compact and versatile format. Though barcodes are cheaper, they require a clear line of sight to be scanned, unlike RFID tags, which can be read from a distance and even in bulk.

Compared to barcodes, RFID systems offer extended range and allow multiple tags to be scanned at once. This enables smooth automation of product handling from warehouse storage to retail shelves. RFID also proves useful for sensitive products like fresh produce and dairy, where shipping conditions must be tightly controlled. For example, RFID models can monitor apple freshness by detecting changes in ethylene, ethanol, and acetaldehyde levels (Lee *et al.*, 2015) ^[70, 71].

RFID technology now supports a wide array of applications in the food industry—from tracking and tracing goods to estimating shelf life, managing the cold chain, overseeing livestock, and even regulating feeding processes (Singh *et al.*, 2022) ^[130]. Some RFID tags are paired with responsive materials in smart labels to offer real-time insights into food quality. When embedded into polymers, RFID tags can detect the presence of biogenic amines (spoilage indicators), changing the electromagnetic signal and alerting handlers or consumers (Grant *et al.*, 2023) ^[43].

Conclusion

Traditional methods used to assess food safety and quality can be slow, labor-intensive, and require skilled professionals. Moreover, they can't prevent problems caused by improper handling or storage-issues that can lead to food spoilage or even poisoning. Smart sensors and automated monitoring systems offer a reliable solution to these challenges.

This is where intelligent packaging steps in. By using simple, low-power devices like RFID tags and QR codes, packaging can do more than just store food—it can communicate vital information about freshness, temperature, and hygiene during transport and storage. This helps ensure safety and traceability and even addresses regulatory concerns like food fraud or trafficking.

Furthermore, non-destructive indicators and sensors with user-friendly designs can be added to commercial packaging to boost shelf life and storage stability. As food technology continues to evolve, these innovations are reshaping how we think about packaging—transforming it into an interactive tool that protects, informs, and reassures both producers and consumers alike.

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