Chapter 14
Packaging Solutions for Monitoring Food Quality and Safety

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1 Introduction

Food safety is a critical issue and all stakeholders involved in the food business, such as manufacturers, retailers, consumers, and regulatory bodies, are concerned about the quality and safety of food products. As the standard of living advances, the consumer's demands and expectations also increase due to lifestyle, increased awareness regarding the importance of nutrients and other quality parameters (Fung et al. 2018). Over a period of time, food packaging has evolved from the simple function of just containing and protecting the food to some important factors that can play an active role in monitoring and ensuring the quality and safety of the food it contains (Risch 2009). Packaging plays a vital role in the preservation and maintenance of food quality during transportation, distribution, storage, retailing and final consumption. Packaging is an art, science, and technology of ensuring the wholesomeness, quality, integrity, and safety of a food product (Kalpana et al. 2019). Due to the increased demand for healthy, safe, convenient, and cost-effective processed foods, the food and beverage industry is compelled to look for more advanced packaging solutions that monitor and ensure food quality and safety. This paved the way for emerging opportunities in scientific and industrial sectors for the development of varied novel technologies in food packaging systems. Among different emerging approaches for developing such food packaging systems, active packaging (AP) and intelligent packaging (IP) technologies are the most promising ones. Hence, owing to the growing interest in the need for innovations in packaging technologies, the chapter details notable and emerging IP systems that enhance food product quality and ensure its safety while being delivered to consumers.

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2 Active and Intelligent Packaging

The advancement in packaging technology is mainly driven by the demanding needs of consumers, which resulted in the development of sophisticated packaging systems with capabilities not only to protect the food it contains but communicate the changes in food or the environment (Yucel 2016). AP is mainly developed by the deliberate incorporation of active components into the packaging itself to release or absorb these active substances into the food or the environment surrounding it and improve the food product quality and shelf life. On the other hand, the IP system does not directly extend the shelf life of food but senses many properties of food and its environment and provides information about the status of food quality to the manufacturer, retailer, and consumer (Gregor-Svetec 2018). IP aims to constantly move together with the entire supply chain and communicate about food and packaging conditions to all stakeholders. IP systems facilitate easy decision-making by providing real-time information about the food products and hence play an important role in ensuring the quality and safety of food products. Figure 14.1 provides an overview of the application of IP systems to maintain the quality and safety of food and food products.

IP systems have the functionality to sense, detect, and/or record internal and/or environmental changes occurring in a food product. The IP systems help in the detection of physicochemical quality, storage condition, microbial stability, and product expiration and freshness of food. IP provides information about the quality, traceability, safety, or tamper indication with the help of different mechanisms (Kuswandi 2017). IP contributes to the improvement in Quality Analysis and Critical Control Points (QACCP) and Hazard Analysis and Critical Control Points (HACCP) systems that are utilized to detect, prevent, control, or eliminate any possible factors that affect the safety and quality of the final food product (Siracusa and Lotti 2019). The IP system functions like an ON/OFF switch that responds to external or internal stimuli and immediately communicates the product status. An IP system is manufactured by incorporating an external component into the food packaging. Most of the IP systems are manufactured by using three main technologies such as (i) sensors, (ii) indicators, and (iii) data carriers.

Fig. 14.1 Illustration of the application of IP systems for monitoring food quality and safety

3 Sensors

The sensor is “a device or tool used to detect, locate, or quantify energy or matter, by giving a signal for the detection or measurement of a physical or chemical property to which the device responds” (Kress-Rogers 1998). A sensor helps in detecting a change in the environment surrounding a food product. The sensor mainly comprises receptor and transducer, where the receptor helps in converting chemical or physical information to an energy form. The function of the transducer is to change the energy to an analytical signal (Sohail et al. 2018). On the basis of transducer working type, the sensors are divided into passive and active types. If a transducer operates with an external power supply for measurement, it is called “active”, or else it is called “passive” (Vanderroost et al. 2014). Sensors also have a signal processing unit and display unit to process the output of transducer and display the quantifiable results in analog or digital form. An ideal sensor should possess high selectivity and sensitivity, rapid response, good reliability, wider dynamic range, complete reversibility, and long-term stability, within miniature size and low manufacturing cost (Ghaani et al. 2016). Mostly, sensors are classified according to the type of receptor, transducer, and their applications, as chemical sensors, gas sensors, and biosensors. Nanosensors and edible sensors are the other newly established sensors. The edible sensor is a novel concept of non-destructive detection of food spoilage. Dudnyk et al. (2018) fabricated a pectin-based edible sensor by combining anthocyanins (red cabbage extract) for principle colorimetric changes and variation in total volatile basic nitrogen (TVB-N) for determining the spoilage in meat-based products.

3.1 Chemical Sensors

Chemical sensors are analytical tools or devices which utilize chemical reagents as recognition elements or receptors. Receptors can identify the presence, composition, concentration, or activity of specific gases or chemical analytes by surface adsorption resulting in an alteration in surface properties. Later, the transducer converts the change in surface property to a quantifiable signal which is proportionate to the target analyte (Kuswandi et al. 2011). Chemical sensors are categorized into gravimetric, optical, electrical, and electrochemical sensors based on their transduction principle (Azeredo and Correa 2021). During IP, chemical sensors are usually used to identify the pH, gases, and volatile organic compounds (VOC), such as carbon dioxide (CO_2) (Borchert et al. 2013), hydrogen sulfide (H_2S) (Sukhavattanakul and Manuspiya 2021), ammonia (NH_3) (Matindoust et al. 2017), dimethylamine (DMA) and trimethylamine (TMA) (Chang et al. 2017) produced during storage and distribution, which could be generated by deterioration of food or loss in integrity of the package. Thus, chemical sensors help in the direct detection of food quality inside the package. Electrochemical sensors are also found to be helpful in quantifying potential toxic additives that migrate from the packaging materials to the food or their toxic products that can form upon contact with the food. For instance, bisphenol-A, that may cause endocrine disorders produced from epoxy resins and polycarbonate bottles (Karthika et al. 2021) and primary aromatic amines generated from isocyanate monomers of polyurethane adhesives are detected with the help of electrochemical sensors (Ghaani et al. 2018). Kuswandi et al. (2012) fabricated a smart packaging system using polyaniline (PANI) film as a chemical sensor for real-time monitoring of the products of microbial breakdown taking place in the head-space of packaged fish. The on-package indicator of PANI film responded with a visible color change to TVB-N released during fish spoilage. The PANI film-based packaging system was recyclable and can be considered as a low-cost sensor for monitoring fish spoilage.

3.2 Gas Sensors

The composition of gas in a food package changes with time and/or temperature as an outcome of physicochemical or biological reactions or leakages (Kuswandi and Jumina 2020). Therefore, the concentration of gas inside a food package gives indirect information about the quality of food. The gas sensors are considered for detecting and indicating gases or volatile compounds like volatile amines, CO_2, H_2S, and other specific gases. Some common gas sensors are electrochemical sensors, optical sensors, field-effect transistors, piezoelectric crystal sensors, metal oxide semiconductors, and organic conducting polymer sensors (Kress-Rogers 1998; Kerry et al. 2006). There are mainly three types of optical gas sensors; fluorescence-based on pH-sensitive indicator, absorption-based colorimetric sensor, and energy transfer approach based on phase fluorimetric detection (Kuswandi and Jumina 2020).

The optical oxygen (O_2) sensors are based on various principles like lifetime decay of O_2-sensitive dyes, photoluminescence absorbance or quenching, and polymeric host quenching. In a study, the phosphorescent dye incorporated reversible optical sensor was used in modified atmosphere packed and vacuum-packed beef. The sensor monitored alteration in O_2 levels, which is kept at 4 °C for about 15 to 35 days for checking the effect of O_2 content responsible for lipid oxidation. In the first instance, the O_2 content was 1.15% and 0.07% and later increased to 1.26% and 0.55% in modified atmosphere packed and vacuum packed beef samples, respectively. The quality, freshness, and safety of beef and chicken stored for 11 days at 4 ° C were evaluated using O_2 sensors. After tenth and ninth day of storage, an intense colour change to red from green was observed in the sensory array of chicken and beef fillets, respectively. The experiment indicated that O_2 sensor can be potentially used for the spoilage detection in meat by revealing promising evidence from the results of freshness, physicochemical, and microbiological tests (Morsy et al. 2014). A new optical O_2 sensor employing micro-structured platinum(II)-5,10,15,20-tetrakis-(2,3,4,5,6-pentafluorophenyl)-porphyrin / polydimethylsiloxane (PtTFPP/PDMS) pillar arrays sensing layers possessing significant sensitivity was fabricated by Mao et al. (2017). The ultrasensitive sensor film exhibited a meagre O_2 detection limit (0.10 μmol/L), which helps in determining dissolved O_2 under the nanomolar concentration range. Also, the improved light intensity-changing characteristics at lower O_2 partial pressure in the sensor aid in the detection of O_2 levels with naked eyes. Similarly, luminescent O_2 sensors based on porous sensing films exhibited highly enhanced sensitivity with improved O_2 accessibility and photoluminescence (Lee and Park 2017). OxySense, a commercially established fluorescence-quenching sensor, utilizes O_2 sensor (OxyDot) placed inside the transparent or semi-transparent sealed package for measuring dissolved or headspace O_2. It possesses non-destructive rapid action to withstand pasteurization temperature without losing sensitivity (Kerry et al. 2006). OxySense is available in varied forms such as tablet, label, or laminate in a polymer film.

The optical CO_2 sensors are used for monitoring the integrity of MAP products. The optochemical sensing techniques usually involve a fluorescence-based system and absorption based on colorimetric sensing. Borchert et al. (2013) manufactured optochemical CO_2 sensors made up of colorimetric pH indicator α-naphtholphthalein and phosphorescent Pt-porphyrin reporter dye, PtTFPP embedded in a plastic matrix along with a phase transfer agent tetraoctyl- or cetyltrimethylammonium hydroxide. The study indicated that the sensor showed the efficacy in measuring headspace CO_2 in MAP foods by retaining its CO_2 sensitivity for 21 days at 4 °C. A very sensitive squaraine-based system for fluorescently and calorimetrically sensing CO_2 in dimethyl sulfoxide (DMSO) containing fluoride ion was developed by Sun et al. (2016). The colour change in response to CO_2 level was visible to naked eyes, with an immense blue shift in absorption (134 nm) and fluorescence (126 nm) spectra. Similarly, an unsymmetrical squaraine-based chemosensor by UV-visible spectroscopy and proton nuclear magnetic resonance spectroscopy in DMSO was also synthesized for detecting CO_2 gas (Xia et al. 2015). Sun et al. (2017), with the help of a highly sensitive "naked-eye" cationic squaraine-based chemosensor, detected CO_2 in an aqueous medium, which might possess a remarkable role in the meat packaging industry. A fluorimetric assay was developed by Khandare et al. (2015) for detecting dissolved CO_2 using an ion-induced assembly of tetraphenylethylene derivatives. Chitosan, because of its amine functionality, was used for the ion-induced assay, and the degree of the aggregation depends on the charge density, which can be compared to the dissolved CO_2 concentration. Chang et al. (2017) conducted a freshness test by quantitatively measuring DMA, TMA, and NH_3 produced by three different types of fresh fish using an amine gas sensor system in contrast to the pre-detected results obtained from organic solid-state semiconductor having 1 min detection period. Likewise, a highly sensitive, flexible, and less energy-consuming NH_3 gas sensor for protein-rich foods was prepared by oxidative polymerization employing polyaniline (a conducting polymer) (Matindoust et al. 2017). Besides, pH-sensitive dyes are also employed for developing gas sensors to detect basic volatile amines in protein-rich foods. A pH-based gas sensing edible film was prepared using anthocyanin extract from red radish, gellan gum, and gelatin, which shows a change in colour from orange-red to yellow in 2–12 pH range (Zhai et al. 2018). The electrochemically written multi-coloured patterns were helpful in real-time monitoring the spoilage in fish and milk. The film indicated black carp fish freshness by the change of film colour induced by the volatile basic gases such as DMA, TMA, and NH_3 produced due to the protein decomposition by enzymes and bacteria. Similarly, the freshness of milk was indicated using film by sensing the gas generated by anaerobic bacteria present in the milk. In another study, an on-package dual-sensor label was developed using bromocresol purple (BCP) and methyl red (MR) as two pH indicators for monitoring the freshness in beef. The decay in beef was determined when BCP changed from yellow to purple, and MR changed from red to yellow. The label responded precisely to the beef spoilage due to pH change in room and chiller conditions (Kuswandi and Nurfawaidi 2017).

3.3 Biosensors

Biological sensor is defined as "a small analytical device or tool that are capable of detecting and recording specific biochemical reactions and converting their presence or concentration into electrical, thermal, or optical signals that can be easily analyzed". Biosensors are effectively used for the freshness indication in meat and fish products by performing pathogen detection and safety systems during food packaging and storage. A representative biosensor comprises a bioreceptor, a transducer, and an electronic system. The bioreceptor recognizes the targeted analyte (microbe, enzyme, nucleic acid, or antibodies), and the transducer converts the biochemical signals into measurable responses (Lloyd et al. 2019). Based on transducer type, biosensors can be categorized as calorimetric biosensors, optical biosensors (luminescent, colorimetric, fluorescent, and interferometric), electrochemical biosensors (potentiometric, amperometric, and conductometric), and mass-based biosensors (piezoelectric and acoustic wave) (Firouz et al. 2021). Among these sensors, an electrochemical biosensor is a promising tool to continuously monitor food quality in IP, generating electrical signals proportional to the concentration of an analyte. The enzyme-based biosensors are the simplest, inexpensive, and user-friendly approach among varied electrochemical biosensors.

The most favourable characteristic for utilizing biosensors in IP is for the identification of volatile compounds like amines, volatile alcohols, and ethylene. In meat packaging, biosensors are used for detecting biogenic amines. Histamines, diamines, and biogenic amines found in rainbow trout meat, poultry, and fish can be identified by employing a putrescine oxidase reactor besides the amperometric hydrogen peroxide electrodes (Ahmed et al. 2018). Biosensors for detecting xanthine (adenine nucleotide degradation product) in animal tissues were manufactured by immobilizing xanthine oxide on electrodes made of silver, platinum, and pencil graphite (Dolmacı et al. 2012; Devi et al. 2013; Realini and Marcos 2014). Xanthine molecules serve as a meat and fish spoilage indicator. For instance, Dervisevic et al. (2015) developed a novel amperometric xanthine biosensor by immobilizing xanthine oxidase by glutaraldehyde over a pencil graphite electrode. The manufactured electrochemical polymerized electrode calculated the xanthine content in the chicken meat, which checked the potentiality of the developed biosensor having high stability, sensitivity, and selectivity. Electrochemical biosensors are employed as glucose sensors to detect the glucose content in varied beverages (Scampicchio et al. 2010). Pesticide detecting acetylcholinesterase biosensor prepared from nafion modified nanoporous pseudo carbon, gold nanoparticles, and chitosan exhibited quick response, agreeable sensitivity, and stability to methyl parathion and organophosphate pesticides at a lower detection limit (Deng et al. 2016). Biosensors have also shown their efficiency in detecting food contaminants like pathogens and toxins.

Several types of biosensors are accessible on a commercial scale for packaging food products. Toxin Guard™ (Toxin Alert Inc. Ontario, Canada) is a biosensor whose functional system is dependent on the integration of antibodies with plastic packaging made of polyvinyl chloride or polyolefins for the detection of pathogens such as *Escherichia coli*, *Listeria* spp., *Salmonella* spp., and *Campylobacter* spp. (Bodenhamer et al. 2004). Food Sentinel System™ (SIRA Technologies, California, USA) is manufactured for certain pathogen antibodies attached to a barcode which is utilized for membrane development. This biosensor helps in detecting pathogenic contaminants by making the barcode unscannable if pathogenic bacteria are present (Food Sentinel System 2019). A flexible biosensor, Flex Alert (Canada), was commercially developed for the detection of toxins in packed foods along with the supply chain. It was explicitly developed for detecting *Salmonella* spp., *Listeria* spp., *E. coli* O157, and aflatoxins (Flex Alert Company 2022). Bioett (Bioett AB, Sweden) is a system technology which integrates electronics and biochemistry for monitoring the temperature of food products in the course of refrigerated transport. It is comprised of a biosensor affixed to the food container, a detector for reading the information obtained from the biosensor, and a database for storing the data regarding the product. The chief components of a Bioett system are a built-in biosensor and a chip-less radio-frequency (RF) circuit (Sjöholm and Erlandsson 2003). However, commercial application of biosensor for IP are insubstantial and needs further development to merge them into food packaging. Nevertheless, the significant challenges in establishing biosensors in IP are the complexity of food structure and trouble in direct measurement of degradation markers in an enclosed package with no antecedent treatment of the food samples.

3.4 Nanosensors

Nanosensors are the sensors made at nanoscale size, having size indicated in nanometers (1 nm = 10^{-9} m) which have structural and functional devices (Kuswandi 2017). These type of sensors helps in IP by involving the use of varied types of nanomaterials like nanoparticles, nanofibers, nanotubes, nanocylinder, nanosheets, and fullerenes (Fuertes et al. 2016). Like sensors, nanosensors are embedded in a food package for controlling the internal and external conditions of the product. Thus, the tiny chip-like nanosensors which are not visible to the human eye aid in detecting chemical contaminants, pesticides, pathogens, spoilage, product tampering, tracing ingredients, and tracking food along the processing chain (Lloyd et al. 2019). For identifying biogenic amines in beer, a very selective optical sensor dependant on covalent interaction between tryptamine molecule and active vinyl groups was developed by Ramon-Marquez et al. (2016). Luminescence signals were generated by the covalently bounded amines because of their intrinsic phosphorescence nature. The developed optical sensor film based on functional non-woven nanofiber mat was known to be highly sensitive and selective for determining the tryptamine in beer. In another study, the nanofibers (150 μm thickness and 300 nm diameter) containing a high concentration of active vinyl groups (330 μmol/g) detected tryptamine in 10 varied types of beers, within 6 ng/ml detection limit. The solid-state polyamide 66 (PA66)/polyaniline nanofiber sensor based on reversible non-redox acid/base doping process detects L-ascorbic acid. It induces visible colour variations even at a low concentration of up to 50 ppb, which can be read using an iPhone (Wen et al. 2015). Such inexpensive sensing films with superior quality can be potentially employed in IP.

Several nanosensors were developed for freshness detection in protein-based foods. For instance, a protein-based halochromic nanosensor was fabricated to evaluate the quality of rainbow trout fillets. The indicator dye, alizarin containing zein nanofibers were prepared by electrospinning. The colour of the nanosensor changes from light purple to magenta by the 12th day of cold storage indicating spoilage. The colorimetric results from the sensor also showed a correlation with chemical and microbial changes in the fish fillets (Aghaei et al. 2020). Recently, intelligent pH-responsive colour indicator films based on cellulose nanofibers (CNF) and carboxymethyl cellulose (CMC) were prepared from shikonin extracted from *Lithospermum erythrorhizon* roots to monitor the freshness of fish. The film exhibited a reddish-pink colour for fresh fish ($pH = 5.7$) and bluish-violet colour for spoiled fish ($pH = 6.9$). The shikonin incorporated films could be likely used for monitoring the quality and freshness of seafood (Ezati et al. 2021). Besides, Ge et al. (2020) prepared a pH-sensitive green nanocomposite film based on black rice bran anthocyanins (BACNs) incorporated oxidized chitin nanocrystals/gelatin. The films exhibited significant colour changes in varied buffer solutions, which could be utilized for monitoring the freshness of hairtail fish and shrimp. Films prepared with low BACNs concentration showed more sensitivity towards basic volatile amines emitted during storage. Hence, the nanocomposite film is a promising sensor for determining the freshness of high-protein foods. Recently, to monitor the H_2S gas concentration, a gas sensor in the form of a hybrid nanocomposite thin film based on bacterial cellulose nanocrystals (BCNCs) was developed. The films were prepared by spraying the hybrid nanocomposite suspension comprising alginate-molybdenum trioxide and silver nanoparticles (AgNPs)-loaded BCNCs over PET substratum. It was observed that the film developed with 1% w/v suspension exhibited the highest sensitivity to H_2S with a 10.94 ppm limit of quantification (LOQ) and 3.27 ppm limit of detection (LOD) when subjected to meat spoilage detection (Sukhavattanakul and Manuspiya 2021).

Carbon nanomaterials are utilized in the manufacture nanosensors because of their light-weight, great mechanical and electrical properties, high flexibility, and high specific surface area (Biji et al. 2015). Carbon nanomaterials are highly sensitive, having a detection limit at ppm levels of gas molecule concentration. Mirica et al. (2013) fabricated an uncomplicated and fast prototyping method by developing selective chemical sensors with graphite and carbon nanotubes (CNTs) on a paper surface. The system depended on the mechanical abrasion of pencils comprising CNTs and small molecules, which may interrelate with certain gases. These nanosensors were able to detect and differentiate vapors and gases at a ppm concentration level. Similarly, the application of printed CNT-based gas sensors was successful with an outstandingly high and quick response to CO_2 and NH_3 (Abdellah et al. 2013). In the foods like pickles and sausages, the nitrate content could be electrochemically sensed with the help of N-doped carbon nanofiber membrane decorated with N-doped graphene quantum dots. The addition of N-doped graphene quantum dots enhances the electron transfer rate, and the N-doped carbon nanofibers imparted a free-standing film structure, greater electroactive area, and electrical conductivity, making the composite suitable for the electrochemical sensors. This quantum dots-based nanofiber sensor with high selectivity, wide linearity range, and outstanding reproducibility exhibited improved efficiency in sensing nitrite with a low detection limit of up to 3 μM (Li et al. 2017). Extensive research in the area of nanosensor has led to significant scientific advancement which paves the way to produce new generation nanosensors that could be promisingly incorporated in IP. However, there are still few concerns regarding the uncertainty in the behaviour and toxicity of nanomaterials with the human body and the further complication it might possess.

4 Indicators

The indicators are semi-quantitative or qualitative devices or tools that give information about the changes taking place in the food or its environment, such as alteration in pH, temperature, time, etc., mainly by a colour change (Yucel 2016). It indicates the presence or absence or the concentration of an analyte or the reaction among two or more analytes (Lloyd et al. 2019). The indicators can be divided into internal and external indicators. The internal indicators are affixed inside the food package (with the lid or in the headspace) like gas indicators or pathogen indicators. In contrast, external indicators are placed on the outer side of the package, such as mechanical shock indicators and time-temperature indicators (TTIs).

4.1 Time-Temperature Indicators (TTIs)

Temperature is a critical environmental factor which determines the kinetics of physical, chemical, and microbial spoilage in foods (Biji et al. 2015). TTIs are the first generation indicators (Bajpai 2019). TTIs are small labels or tags which track the time-temperature of perishable products from production to consumption. TTIs function depending on the temperature changes in the product or the package. It measures and displays the same on the IP system. TTIs determine and exhibit information about when the food has been exposed to a higher temperature than the desired range during storage and transportation, which is very important to know the temperature abuse for frozen or chilled food products (Pavelková 2013). TTIs can be categorized into three main classes on the basis of their function, temperature history, and operating principle. Based on the function, TTIs are further divided into critical temperature indicators, time-temperature indicators, and critical temperature/time integrators. Critical temperature indicators depict the organoleptic changes and deterioration of food when exposed to temperatures below or above the specified ranges for more than a mentioned time interval via visible but irreversible colour changes of the indicator. Critical temperature/time integrators exhibits a response above a reference critical temperature that could be interpreted with regard to equivalent exposure time at that critical temperature, thus indicating the safety and quality of the product (Taoukis and Labuza 2003). The third type, TTIs shows the overall influence of temperature history on the quality of the product from the manufacture to utilization by the consumers (Janjarasskul and Suppakul 2018). On the basis of temperature history, TTIs are divided into partial history indicators and full history indicators. A partial history indicator gives an indication only when the food is exposed to a higher temperature than its critical temperature. In contrast, a full history indicator furnishes information regarding the food packaging over time (Kerry et al. 2006). Lastly, TTIs are categorized on the different working principles, such as chemical, enzymatic, mechanical, electrochemical, and microbiological principles, usually shown with a change in colour or change in intensity of the colour (Müller and Schmid 2019). In the previous years, the industrial use of different indicators, for instance, diffusion-based TTIs, enzymatic TTIs, microbial TTIs, polymer-based TTIs, and photochromic TTIs have been increased significantly for evaluating the time-temperature of varied commercially developed perishable foods products. Table 14.1 depicts some prominent TTIs that were commercially utilized for varied food products based on different working principles.

Kim et al. (2016) developed isopropyl palmitate (IPP) diffusion-based TTI for determining the microbiological quality in unpasteurized angelica juice. The experiment reported that IPP diffusion up to 7 mm in the TTI showed effective identification of microbial spoilage in the sample when the TTI was used at a temperature 13 °C or higher. Besides, an economical and accurate polymer-based TTI functioning on pH changes was prepared from chitosan, polyvinyl alcohol (PVA), and *Brassica oleracea* (red cabbage) extract. The prepared TTI was able to sense the

Table 14.1 List of some commercial TTIs

Product name	Manufacturer	Operational principle
3M™ MonitorMark®	3 M Company, USA	Molecular diffusion
3M™ Freeze Watch™	3 M Company, USA	Molecular diffusion
CheckPoint®	Vitsab International AB, Sweden	Enzymatic reaction
CoolVu™	Evigence Sensors™, Haifa, Israel	Dissolution process of a fine aluminium layer
Fresh-check®	Temptime Corporation, USA	Solid-state polymerization reaction
Keep-it®	Keep-it technologies, Oslo Norway	Chemical reaction
TempDot®	DeltaTrak, California, USA	Indicates cumulative exposure above temperature threshold
Timestrip® PLUS	Timestrip Plc, Cambridge, UK	Solid-state polymerization and enzymatic reactions
TopCryo™	TRACEO, France	Microbiological reaction
OnVu™	Ciba Speciality Chemicals, Switzerland and Freshpoint, Switzerland	Photochemical reaction
WarmMark®	DeltaTrak, California, USA	Indicates cumulative exposure above temperature threshold

change in pH in the pasteurized milk and showed visual indication by changing the colour (Pereira et al. 2015). Lee et al. (2019b) developed an air-activated TTI for monitoring the shelf life of sandwiches stored for 63 h at 5 °C. The developed TTI worked based on the redox reaction between colorimetric material (leuco methylene blue) and redox reaction repressor (a mixture of L-cysteine and L-ascorbic acid; AC) and in the presence of O_2.

The microbial TTI response shows direct relation with microbial spoilage in food. A correlation can be determined between microbial growth in food and microbial growth and its metabolism in the respective microbial TTI. Microbial TTIs are now increasingly applied to determine the shelf life and quality of perishable foods stored in the cold chain. A microbial TTI was fabricated for vacuum-packed giant grouper (*Epinephelus lanceolatus*) fillets by Hsiao and Chang (2017). The team selected *Lactobacillus sakei* as the main spoilage bacteria for the vacuum-packed fish fillets and observed the biochemical and microbiological changes in the samples. The microbial TTI was reported to be effective for monitoring the freshness of marine products, as it indicated three grades of freshness, such as “very fresh”, “fresh”, and “spoiled”, on the basis of TVB-N levels. Mataragas et al. (2019) developed an efficient microbial TTI using *Janthinobacterium* sp. which has the potential to form a violet pigment, violacein during its early growth by depending on the intrinsic properties and temperature of the growth medium. The bacterium was spot-inoculated in 1% glycerol incorporated tryptic soy agar to fabricate the microbial TTI. Under dynamic and isothermal storage, the TTI device was used to validate spoilage in minced beef employing the data generated from the experimental analysis. They observed a noticeable effect on the initial concentration of

Janthinobacterium sp., spot quantity, and pH of the growth medium related to the different endpoint times and Arrhenius activation energy (Ea) of the TTIs, indicating the flexibility of the intelligent device.

The enzymatic TTIs are more susceptible to changes in environmental temperature and show increased precision than physical diffusion TTIs and microbial TTIs. Giannoglou et al. (2019) conducted a study to select appropriate enzymatic TTIs for monitoring the shelf life and quality of ready-to-eat smoked fish products in refrigerated storage. The enzymatic TTIs response was kinetically modeled and correlated with the quality and shelf life of cold-smoked salmon, and vacuum-packed hot smoked rainbow trout, and European eel in the cold chain. The experiment stated that the developed TTI designs, M-17 U, LP-17 U, and M-5 U determined the shelf life of vacuum-packed smoked salmon slices, smoked trout, and eel fillets at 5 °C for 2, 11, and 7.5 weeks, respectively. A novel solid-state enzymatic TTI after isothermal verification was made by 5 g amylose, 0.02 g glucoamylase microcapsules, 0.1 M iodine solution, and 2 mm thickness agar cover. The formulated enzymatic TTI was used to know the time-temperature history of chilled fresh pork with the help of colour indication. The kinetic properties and spoilage mechanism of pork samples were determined, and the Ea was found to be 64.7 kJ/mol (Meng et al. 2018).

There are different types of TTIs that are commercially developed and patented. They are primarily based on diffusion, chemical, enzymatic, biological, microbiological, and polymerization reactions. Figure 14.2 represents a schematic representation of commercially employed TTIs in the market. Nonetheless, the TTIs based on diffusion systems govern the IP market due to certain limitations in enzymatic TTIs, such as enzymatic instability and high cost. Even though different TTIs have been developed for meat, fish, dairy, and frozen products by evaluating the storage characteristics, the research regarding TTIs for liquid foods is still limited and requires further exploration.

4.2 Gas Indicators

Gas composition inside a food package should be carefully monitored, as any alteration in it from the standard composition may lead to product spoilage. The gas indicators in the form of labels are usually inserted in the package for determining the changes of the inside atmosphere (Ghaani et al. 2016). Alteration in the composition of the gas is caused by various factors such as leakage in the package, respiration of the produce, chemical or enzymatic reaction of the food matrix, microbial permeation through package, or production of gas by microorganisms (Sharma and Ghoshal 2018). Thus, a gas indicator is a small device placed inside or printed outside a package that responds to gas composition changes and indicates the integrity, quality, and safety of packaged food products (Fang et al. 2017). Mostly, the concentration of O_2, CO_2, or ethylene (C_2H_4) is indicated by colour change of the label (Sohail et al. 2018). However, water vapour, H_2S, ethanol (C_2H_5OH), NH_3, DMA, and TMA are accessed for spoilage determination.

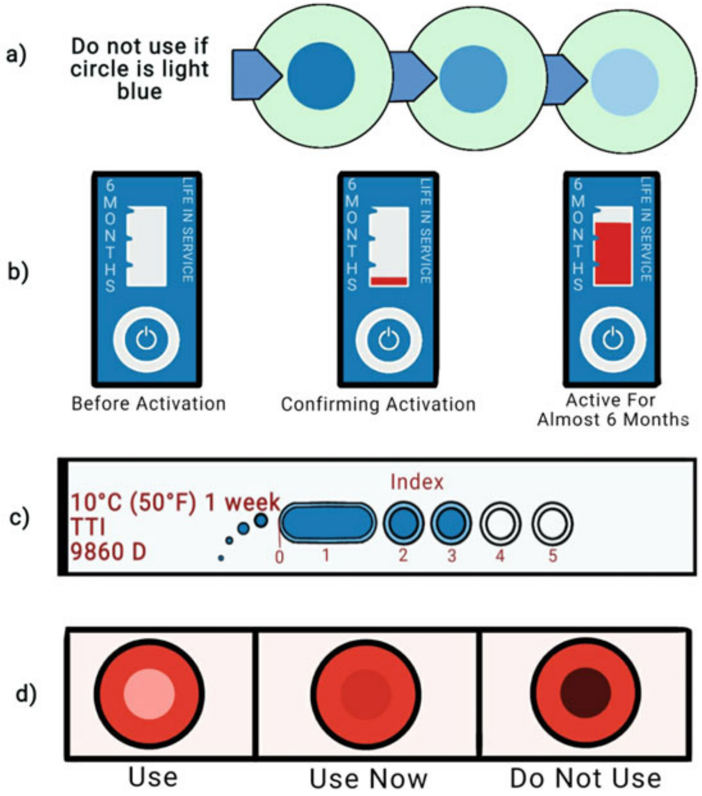

Fig. 14.2 Schematic representation of commercially used TTIs

The most widely employed gas indicator is the O_2 indicator as it indicates the quality of food by colour change, oxidative rancidity, and microbial spoilage (Fang et al. 2017). The O_2 indicators are of two types; colorimetric and luminophoric. The colorimetric system works on the principle of colour change by redox reaction, light-activated redox reaction, or O_2 binding reaction, while the luminescence intensity is an indicator of the presence of O_2 inside the package in a luminophoric system (Sharma and Ghoshal 2018). For example, Yılmaz and Altan (2021) developed a colorimetric oxygen indicator using functionalized electrospun polystyrene (PS) fibers by the process of electrospinning. Meatball samples that were packed with the indicator exhibited quick and remarkable changes in the colour of the indicator in the presence and absence of O_2. The fabricated oxygen indicator which is resistant to dye leakage also showed minimal in-pack activation time. CO_2 indicators are commonly employed for monitoring the CO_2 concentrations in MAP foods. It helps in identifying the incorrectly packaged products for immediate repacking, reducing time-consuming and labour-intensive quality control procedures (Fang et al. 2017). Lately, many works have been conducted for fabricating CO_2-sensitive smart packaging films. As the CO_2 percent inside the headspace of the package elevates, the film colour changes to show a visual index of packaged food quality. Similar to change in O_2 concentration, change in CO_2 also accelerates microbial spoilage. Also, like O_2 indicators, colorimetric CO_2 indicators can be prepared from natural extracts for determining the variations in pH. Saliu and Della Pergola (2018) developed a colorimetric CO_2 indicator from a mixture of lysine, ε-polylysine, and naturally occurring dye, anthocyanin, to determine the pH changes in MAP packages. The indicator functions depending on the formation of carbonic acid derivatives via an irreversible reaction. The researchers observed visible colour change with the change in CO_2 when both the label and aqueous type indicators were tested against poultry meat. The study indicates that the developed indicator can be used as a colorimetric CO_2 indicator for cold preserved foods.

The quality of kimchi can be monitored by developing a poly (ether-block-amide) (PEBA) film-based CO_2 indicator. The indicator prepared from PEBA film, bromothymol blue (BTB), and MR displayed alteration in CO_2 concentration in the package's headspace. The colour change of the indicator is the function of the CO_2 present in the package, which was correlated to the proportion of the materials employed in the package. From the fabricated indicators, the highest total colour difference (TCD) value was reported in the indicator made of PET/PEBA + dye (MR + BTB) (3:7) + polyethylenimine (PEI) 5%/PEBA, which was concluded as the most efficient indicator for monitoring the quality of kimchi (Baek et al. 2018). Howbeit, the incorporation of these dyes in the packaging materials leads to the migration of dyes into high-moisture food matrices. Hence, Lyu et al. (2019) fabricated a branched PEI incorporated (BTB^-)/tetrabutylammonium (TBA^+) ion-paired dye to prepare CO_2_sensitive intelligent films. The developed multi-layered packaging films were utilized for determining the change in CO_2 level in packaged kimchi during its fermentation process. The CO_2-mediated colour change was visible to the human eye, explaining its potentiality in developing commercial IP.

The TVB-N content is a crucial factor when observing the freshness of pork. For example, a colorimetric label was made to evaluate the shelf life of packaged lean pork in cold storage for 8 days. The indicators were made from three varied pH-sensitive dyes; BCP, BTB, and a blend of BTB and MR. The freshness indicators were prepared by combining polyethylene glycol-6000, methylcellulose, and dye solution in distilled water. The biochemical reactions and microbial spoilage are two major factors that affect the freshness of pork. The result of principal component analysis and TCD performed using colorimetric data of various indicators reported that indicator made up of BTB and MR (3:2) discriminated pork as "fresh" (red), "medium fresh" (golden rod), and "spoiled" (green) during cold storage (Chen et al. 2019). Recently, to monitor the freshness of chicken breast stored at 4 °C, Yildiz et al. (2021) developed an IP system from natural halochromic curcumin loaded chitosan/polyethylene oxide (PEO) nanofibers. Depending on the freshness of chicken breast, the pH sensor film changed the colour from bright yellow to red, easily detectable by the naked eyes. After the storage period of 5 days, the TVB-N concentration was 23.45 ± 3.35 mg/100 g indicating the sample was at the edge of the acceptance level. As a result, the curcumin loaded-nanofibers help to perform the real-time monitoring of chicken.

4.3 Freshness Indicators

The chemical and microbial deterioration affects the freshness of food; thus, chemical and microbiological spoilage in food occurring during handling and storage of food are determined by a freshness indicator (Sharma and Ghoshal 2018). Freshness indicators are primarily internal indicators placed inside a package for indicating the freshness and quality of food by changing their colour. Besides determining the food quality and deterioration, freshness indicators are utilized to estimate the shelf life of the product. The quality indicating metabolites are CO_2, C_2H_5OH, glucose, organic acids, volatile nitrogen compounds, biogenic amines, sulphuric compounds, and ATP degradation products (Müller and Schmid 2019). Freshness indicators are mostly used in products like fresh meat, seafood, and fruits. Each freshness indicator is specific to the product. For instance, a freshness indicator developed for seafood will show a response when volatile amines are produced. Similarly, freshness indicators for chicken, beef, and other protein-based foods are prepared using biogenic amines like histamine, tyramine, cadaverine, and putrescine. TMA and TVB-N also aid in indicating the freshness of meat products.

Freshness indicator in the form of a label using BTB and MR (2:3) was used for real-time monitoring of green bell pepper stored at 7 ± 1 °C. As the CO_2 in the IP increases, the indicator exhibited an intense change in colour to orange from yellow-green (Chen et al. 2018). Similarly, a pH-sensitive dye-based colorimetric indicator label was developed to monitor the freshness in skinless chicken breast. During storage, the CO_2 produced was considered a spoilage indicator and showed higher concentration than TVB-N. The indicator correlated with an increase in CO_2 level and microbial growth in the stored sample and exhibited the variation in CO_2 level by colour change in the IP (Rukchon et al. 2014). Lee et al. (2019a) manufactured an inexpensive and simple freshness indicator for monitoring spoilage in chicken breast made of three-layered structure and porous Tyvek® sheet for improved gas and water vapour permeation. The indicator solution composed of BCG was coated over the low-density polyethylene (LDPE) films and later laminated on Tyvek® sheets. The colour change of the freshness indicator containing chicken breast was correlated with bacterial growth and TVB-N and CO_2 contents in the chicken breasts. The changes in the indicator were captured as digital images using a smartphone camera and examined with the help of RGB pixel intensities. The colour change from green to yellow indicated sample spoilage by showing a remarkable difference in RGB values. Thus the developed high-confidence freshness indicator is a reliable, user-friendly approach to monitor the quality changes in fresh chicken breasts.

The aging in cod flesh was examined using an indicator made of beetroot, grape peel, and curcumin extracts. The volatile amine was monitored by the indicators prepared from these natural dyes and compared with the functionality of indicator designed with artificial dye, MR. Out of all the three natural dyes, the indicator made of grape peel extract and curcumin showed comparable results with the MR-based indicator by indicating a colour change with TCD values equal to approximately 30 units correlating the cod flesh spoilage (Tichoniuk et al. 2017). For determining the freshness of silver carp (*Hypophthalmichthys molitrix*) stored at refrigeration temperature, Zhai et al. (2017) fabricated roselle (*Hibiscus sabdariffa* L.) anthocyanins incorporated starch/PVA colorimetric film. The films represented as an IP device by indicating visible colour changes over time showing the occupancy of TVB-N. The rancidity reaction of O_2-sensitive dairy products was determined using a colorimetric indicator. An indicator made up of MR and BTB was used for accelerated shelf life in the milk powder formula stored at 30 °C. The indicator responded via a visible colour change from light green to orange to the volatile compounds, acetic acid, and hexanal developed during hydrolytic and oxidation reaction during storage. The accelerated shelf life in milk powder was observed to be 26 days, and the orange colour indicated a sign of either rejecting or warning (Kulchan et al. 2016).

The pH-based indicators work as freshness indicators by changing the colour for indicating the presence of various metabolites. A direct-contact type freshness indicator was used for real-time monitoring chicken breasts based on the variation in pH. The indicator comprised of BCP was immobilized with PVA on a high absorbance pad (Kim et al. 2017). This type of intelligent device can be utilized as either a freshness indicator or a high sensitivity shelf life determination tool. Liu et al. (2019) developed a *Lycium ruthenicum* Murr. extract incorporated κ-carrageenan colorimetric films as a pH indicator in intelligent packaged milk for assessing its freshness. The indicator showed a reversible colour change from pink to colourless over the pH range, 2–10, specifically pink to colourless with the pH, 2–6, and blue-purple to yellow with the pH, 7–10. The film was also acceptable for indicating the freshness of aquatic food products.

Another intelligent tool for indicating the food quality and freshness is the ripe sensor. With regard to fruits, their freshness is related to the degree of ripeness they possess. One such commercially employed freshness indicator is the RipeSense®, an ethylene gas indicator manufactured by the Jenkins Group and the Plant & Food Research, Auckland, New Zealand (RipeSense® 2004). RipeSense® is the world's first intelligent label sensor which indicates the change in ripeness of a fruit of the package by changing the colour of the package. The fruit generates a characteristic aroma as the process of ripening initiates. The sensor element responds to the released aroma compounds and results in changing the colour of the intelligent device. Firstly, the colour of the label is red if the fruit is unripe, and later on, during ripening, it changes to orange and turns yellow, indicating a fully ripe fruit. The illustration of the function of the RipeSense® freshness indicator in fruits is depicted in Fig. 14.3. Currently, RipeSense® is used for monitoring the freshness of various fruits like pears, apples, kiwi, melon, avocado, mango, and stone fruit. Table 14.2 summarizes commercially manufactured gas and freshness indicators used for monitoring food safety and quality.

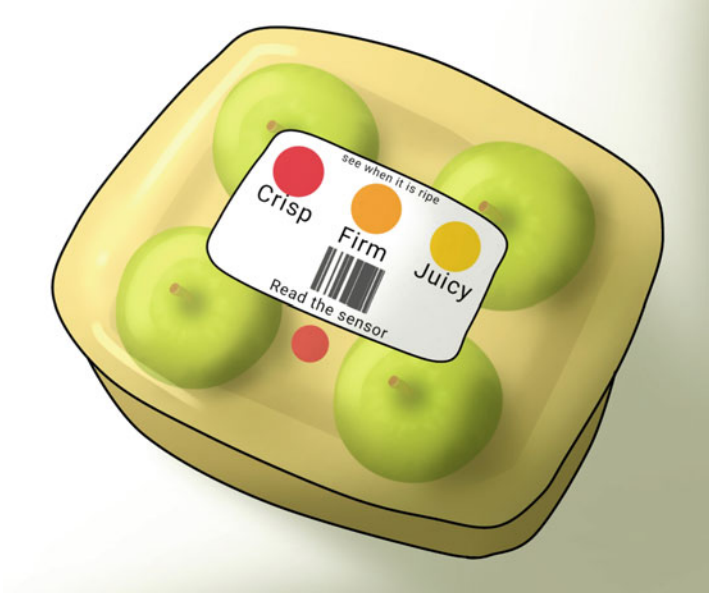

Fig. 14.3 Illustration of the function of RipeSense® freshness indicator in fruits

Table 14.2 List of some commercially developed gas and freshness indicator

	Product name	Manufacturer
Gas indicators	Ageless Eye®	Mitsubishi Gas Chemical Inc., Japan
	Best-by™	FreshPoint Lab
	Freshilizer	Toppan Printing Co., Tokyo, Japan
	Novas®	Insignia Technologies Ltd., West Sussex, UK
	O_2 Sense™	FreshPoint Lab
	Shelf Life Guard	UPM-Kymmene Corporation, Finland
	Tell-tab	IMPAK Corporation, Los Angeles, USA
	Tufflex GS	Sealed Air Ltd., USA
	Vitalon	Toagosei Chemical Inc., Tokyo, Japan
Freshness indicators	Food Fresh™	Vanprob Solutions
	Food Sentinel System	SIRA Technologies Inc., California, USA
	Fresh Tag®	COX Technologies, USA
	SensorQ™	Food Quality Sensor International Inc., Massachusetts, USA and DSM NV, Heerlan, Netherland
	Raflatac	UPM Raflatac, Scarborough, UK and VIT Technical Research Centre, Finland
	RipeSense®	Jenkins Group, New Zealand and Plant & Food Research, Auckland, New Zealand
	Toxin Guard	Toxin Alert Inc., Ontario, Canada

5 Data Carriers

Automatic identification devices also known as data carriers, helps in ensuring the automatization, traceability, and counterfeit protection throughout the supply chain by storing and transmitting the product information regarding storage and distribution (Müller and Schmid 2019). Traceability assures food safety by attaining a better market as it provides the complete history of a package with the help of barcodes and radio-frequency identification (RFID) tags (Chen et al. 2008).

5.1 Barcodes

The most popular data carrier is the barcode, which is an inexpensive simplest machine-readable storage database which works on the optical phenomenon of vertical code bars placed at systematic thickness and width (Kalpana et al. 2019). On scanning a barcode, the laser beam moves over the symbol and measure the relative time it uses to scan the dark bars and light spaces (Ghaani et al. 2016). Mostly the barcodes on the products are assigned in numbers and character forms. The barcodes are widely classified into two types; 1D and 2D. 1D barcode is a simple linear arrangement of black and white bars which are simultaneously placed to store data and information. This type of barcode can only hold about 10–13 characters or 2953 bytes of information (Firouz et al. 2021). On the other hand, a 2D barcode uses two-dimensional geometrical patterns. 2D barcodes have the capacity to store about 7089 numeric and 4296 alphanumeric characters. Presently, the most frequently used 2D barcodes are Data Matrix, QR code, and PDF 417 (Bajpai 2019). The first commercialized barcode, Universal Product Code (UPC), having a pattern of lines and spaces, is still successfully utilized in the market. Another type of the barcode is the Reduced Space Symbology or GS1 DataBar™, which was invented to meet the reduced space usage requirement in the product packages (Uniform Code Council 2014). Besides, Content Idea of Asia Company (Kuwana-shi, Mie-ken, Japan) in 2006 launched a barcode named PM code. It is a three-dimensional colourful QR code, where its third dimension is coloured (PM Code 2006). Chen et al. (2017) developed a simple, cost-effective barcode, a colour-based sensor array formed in silica beads using the dyes, zinc tetraphenylporphyrin (TPP), MR, and Nile red in three dissimilar geometric shapes for detecting the spoilage in chicken. The detection of spoilage was found by the separation of green, blue, and red dyes which is read with the help of a built-in app designed on a smartphone. On storage, if the pathogen develops inside the package, it can be detected by the barcode and with the colour changes, which makes the barcode unreadable.

5.2 Radio-Frequency Identification (RFID) Tags

RFID tags utilize electromagnetic fields for storing and communicating real-time product information for automatic product identification and traceability (Realini and Marcos 2014). It is widely obtained as a form of chip made of tags used for storing data (Kalpana et al. 2019). RFID has shown its application in almost all food products including, meat, seafood, fruits and vegetables, beverages, bakery, and dairy products. RFID systems provide several advantages such as automatization, product traceability, prevention of product recalls, minimized counterfeit, theft prevention, reducing labour cost, and inventory management. These systems with about 1 MB storage capacity can hold more complex information like relative humidity and temperature, nutritional information and cooking instructions (Ahmed et al. 2018). An RFID system consists of three main elements; tag, reader, and middleware. A tag is made up of a microchip for storing data which is joined to an antenna. The reader sends radio signal and receives the response from the tag. The middleware is the web server or local network responsible for connecting the RFID hardware with their applications (Kuswandi and Jumina 2020). An RFID middleware filter, integrate data, coordinate reader, and manage the scheduled processes (Chen et al. 2008). Figure 14.4 shows a schematic representation of a RFID system. The RFID systems are classified into three types; active RFID tags, which require battery-powered tags for broadcasting signal to the reader; semi-passive RFID tags, which employs battery to power the tag for modulating the waves emitted by the reader; and also for maintaining the memory of the tag; and passive RFID tags, which are simple and short-range, are powered by a reader that does not require any battery (Ilie-Zudor et al. 2006).

The sensor-enabled RFID tags have shown their promising application in storing and transporting perishable commodities like fruits and vegetables, milk, fish, meat, and poultry which need strict environmental conditions. The combination of sensor technology and RFID helps in improving the efficiency of supply chain management and reduces waste production. Sen et al. (2013) developed a RFID system along with gas and temperature sensor for detecting the freshness and quality of pork meat. The

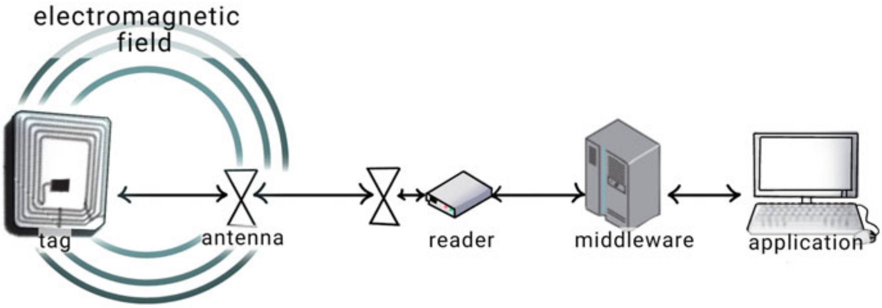

Fig. 14.4 Schematic representation of RFID system

system categorized meat quality as “great”, “medium”, “low” and “corrupt”. In the study, the concentration of H_2S generated from the meat was evaluated at varying temperatures to find its relation with meat spoilage. Correspondingly, the reader received the H_2S concentration and sent the data to the display screen. Thus, the seller or the consumer can read the meat quality. In the case of seafood, a printable smart RFID tag was used for detecting and examining the fish spoilage by knowing the levels of volatile amines and humidity. Besides, anisotropic conductive adhesives (ACA) was employed as the integrated chips. Smits et al. (2012) developed an RFID system of low power-consuming MSP430G microprocessors for studying the freshness of cod fish by evaluating the humidity, temperature, and volatile amine compounds at 5 °C for an interval of 2 min. The study reported that the developed system did not depend on the type and quantity of fish but relied on the freshness indicating factors. Similarly, Abad et al. (2009) demonstrated a RFID smart tag for cold chain monitoring and real-time traceability of intercontinental cold logistic chain of fresh fish. The experiment revealed that the developed system showed supremacy compared to conventional traceability tools by showing no human participation, reusability, more memory, ability to read many tags at a time, and more aversion to humidity and other environmental conditions.

A unique chipless RFID sensor system for wireless sensing was manufactured by Amin et al. (2016). The system was easy to use, requires no maintenance, and works without any electrical source unlike other RFID systems. Recently, Alfian et al. (2020) developed a RFID-based traceability system furnished with internet of thing (IoT) sensor for monitoring and knowing environmental conditions, namely, humidity and temperature for perishable food distribution during storage and transportation. This system communicated counterfeiting and low-quality food products along the supply chain by enhancing the traceability with the developed machine-learning model into RFID gate for automatic identification of the direction of tagged products. RFID systems have also been assisted with indicators for ensuring quality and traceability of foods. For instance, RFID was integrated with critical temperature indicators for fresh-cut fruits (Lorite et al. 2017); RFID was integrated with optical indicator for tracing kiwi fruit (Gautam et al. 2017); and for monitoring O_2 concentration (Martínez-Olmos et al. 2013).

A few reusable TT sensor tags fabricated to show the temperature history of products throughout the cold chain process are the TempTRIP sensor tag (TempTRIP 2012), sensor tag CS8304 (Convergence Systems Ltd.) (CLS 2013), and Easy2log© (CAEN RFID Srl) (CAEN RFID 2014). Manufacturers have also integrated the RFID systems into the food box in the packaging industry. The Intelligent Box presented by Mondi Plc is a RFID-enabled corrugated case which is furnished with a RFID tag at the case level for tracing it throughout the supply chain (Mondi 2011). Besides, the Craemer Group GmbH has manufactured an intelligent fish box. The fish box is composed of an integrated RFID transponder which helps in identifying, tracing, and tracking information regarding the size and quality of fish, and fishing grounds to ensure absolute traceability of fish catches (Craemer 2014). NXP® Semiconductors Company (Eindhoven, Netherlands) fabricated wireless sensors based on RFID systems to monitor packaged food products.

The environmental parameters like C_2H_4, CO_2, and O_2 were evaluated, and the documented information was sent to the central system (NXP® Semiconductors 2022).

6 Other Intelligent Tools

Another type of intelligent devices drawing increasing interest to ensure food safety and quality, and to prevent counterfeiting and tampering are the thermochromic inks, holograms, internet of everything (IoE), carbon photonics, organic photonics and electronics, and printed electronics.

6.1 Thermochromic Inks

Thermochromic ink is an activated ink which changes its colour when exposed to varying temperatures. These inks are usually employed in microwave food products or beverage packaging that allows the consumers to be aware if the food is to be served hot or cold (Sohail et al. 2018). The colour change of the ink is either reversible or irreversible. Irreversible inks are not visible until it reaches a specified temperature, and once the colour appears, it stays unchanged if there is no shift in recorded temperature. If the temperature shoots up, the colour changes and leaves a temperature change indication (Roya and Elham 2016). Whereas reversible thermochromic inks change its colour when heated and returns to the initial state as the temperature decreases. There are also few other variations in the type of thermochromic inks. The cold-activated thermochromic inks are employed on a packaging label for creating a change in colour when the food is cooled. The touch-activated thermochromic inks show an image or another colour printed below once touched or rubbed. High-temperature thermochromic inks switch their colour just beneath the pain threshold, alerting customers regarding a safety hazard. Thermochromic inks are manufactured by different companies like QCR Solutions Corp. (USA), CTI Inks (USA), LCR Hallcrest (USA), B&H Colour Change (UK), and Siltech Ltd. (UK).

6.2 Hologram

A hologram is an emerging and attractive tool applied in food IP, which aims to safeguard the brand name of the product and avoid counterfeiting and tampering with the product (Sohail et al. 2018). The pattern changing of the hologram deprives the counterfeiters to change the product label or the product. However, if the counterfeiters try to remove the hologram, the upper polyester film of the package should be taken off, thus leaving a mark that indicates product tempering (Pareek and Khunteta 2014). Even though holograms are widely used for expensive drugs in the pharmaceutical industry, their utilization in food IP is limited. The existing technological development of IP system in food industries promises more comprehensive future application of holograms to ensure food safety.

6.3 Internet of Everything (IoE)

In the era of IoE, besides the basic functions of packaging, including storage, transportation, and protection, the design of modern transport packaging should be considerably made using eco-friendly and recyclable packaging systems (Zhang and Peng 2019). The IoE is a relatively novel concept that aims at a world-wide network of interconnected objects. Such a system is made possible by the integration of varied state-of-the-art technologies and communication devices like wired and wireless sensors, RFID tags, GPS, and enhanced communication protocols (Vanderroost et al. 2014). Rather than remotely monitoring the food quality and package integrity, it is foreseen that IoE in due course, result in the advancement in food safety management, QACCP, and HACCP systems (Takhistov 2009). This development in IP may gradually help in identifying potential safety hazards and conducting biohazard analysis, recommending controls and critical limits, and monitoring food loss on an international scale. Although IoE is a relatively growing technology in food industries, more comprehensive application of this technology can be expected in the near future.

6.4 Carbon Photonics

Carbon-based nanomaterials are known to show excellent mechanical and electrical properties and exhibit distinctive optical properties that can be utilized to manufacture future optical sensors as a substitute to silicon photonics (Vanderroost et al. 2014). For instance, Kruss et al. (2013) reported the first research work using carbon nanomaterials for the development of optical biosensors. Carbon-based nanomaterials can also be modified chemically so that biologically relevant molecules can be determined with excellent selectivity and sensitivity. The role of external electric fields, electrical and optical mechanisms of their production, non-radiative and radiative decay modes, and their potentiality in technological use as nano-sized light sources, photodetectors or photovoltaic devices (Avouris et al. 2008). Besides, the so-called carbon dots (CDs) are regarded as the class of strongly fluorescent and emission colour tuning carbon nanomaterials with high analytical and bioanalytical potential (Esteves da Silva and Gonçalves 2011).

6.5 Organic Photonics and Electronics

Organic photonics and electronics investigate how electrical and optical circuits could be combined with organic materials (e.g., polymers) instead of silicon with no compromise on the circuit size. Organic photonics and electronics aim to exhibit similar or advanced electrical or optical characteristics with improved mechanical properties (Vanderroost et al. 2014). The photonics system as printed elements ensures the functionality of novel packaging systems, AP and IP by informing the status of a packaged food by altering the internal or external sensor properties. The changes in the packaging system can be instrumentally or visually registered using internal or external devices. Development of photonics system and future simulation, understanding the printing techniques of printed elements, and preparation of functional surfaces containing these systems need to be convincingly carried out, ensuring the functions of IP systems (Sarapulova et al. 2015). Organic photonics and electronics hence enable energy-efficient creation of IP merged with ICT. This area of research also leads to the design and development of novel organic materials for IP.

6.6 Printed Electronics

Printed electronics are the flexible printed sensors holding a receptor on top of a printed transducer (Lloyd et al. 2019). Light-weight, portability, bendability, and foldability are few individual properties of printed electronic sensors (Biji et al. 2015). This packaging solution allows printing over varied substrates (such as steel, paper, polyethylene terephthalate (PET), polyimide, polyether ether ketone (PEEK), transparent conductive polyester, etc.) by electrically functional inks and shows them as a unique and tailor-made sensor for packaging food products (Lloyd et al. 2019). The flexible printed chemical sensor, comprising a receptor printed over a transducer, shows promising possibilities to revolutionize the development and utilization of IP systems. The printing techniques for producing printed electronics are screen printing, ink-jet printing, and gravure, where each method shows different advantages and limitations, depending on the product and the purpose.

7 Global Market and Legislative Aspects of Intelligent Packaging

The primary objective of innovative packaging solutions is to adopt varied packaging technologies to reduce food spoilage and food waste. Such technologies are adopted to cope with the augmenting demands in food safety, brand differentiation, and stock management (Realini and Marcos 2014). From the studies so far, it is evident that IP helps enhance the quality of food, reduce food wastage, and improve overall food production efficiency. The market for intelligent, active, and advanced packaging has increased at a compound annual growth rate (CAGR) of approximately 5.8%, in which IP showed around $ 5.3 billion in sales in 2017 (BCC Research 2013). However, the application of IP in the food sector is still limited because of its high cost and restricted integration with other packaging systems. The legislative aspects and perceptions of consumers are considered before implementing a new IP in the market.

One major issue which deprives the acceptance of intelligent devices in the market is the reluctance of consumers to encourage the non-edible items separate from the package. The prejudiced approach of consumers to innovative packaging applications might misguide them about the actual product quality. The beneficial part of IP systems is still unclear as the consumers find the inserts, sachets, dots, and spots to be unnecessary in a food package. The contaminants that could be observed from IP materials include inks, adhesives, resins, pigments, oils, solvents, stabilizers, surfactants, plasticizers, antimicrobials, antioxidants and other additives (Mirza Alizadeh et al. 2021). The risk of accidental consumption or leaching of active components (e.g., inks) to food from an intelligent device when affixed with the primary packaging material creates a concern of food safety and health among the consumers. Consequently, the identification of substances that can possibly be released from the packaging system is important due to their impact on product quality and consumer safety. The release of intelligent substances from IP should be considered in terms of their toxicity, and their migration should comply with food legislative aspects. The migration of materials can be determined by migration tests or by adapting mass transfer modelling tools.

Japan, Australia, and the United States have shown the widespread application of IP systems in food industries, while Europe has implemented certain legislative regulations which hinder the integration of novel packaging technologies into the market. The first law regarding the materials considered to come in contact with food came in 2004 (European Commission 2004). Specifically, the law aimed to focus the human health versus the safety of the packaging materials, stating that any foreign component in the package should not transfer to the food in impermissible quantity, making unsatisfactory changes in the composition and organoleptic properties of food. Besides, IP systems employed in food packaging should not provide misleading information to the customers, and their suitability to food contact and appropriate use should be clearly mentioned. Nevertheless, in 2009 a list was published containing the authorized substances which can be allowed to have food contact and can be used for the production of active and IP systems (European Commission 2009). In addition, this law stated that when either active or intelligent devices are employed in a food package, it is compulsory to mention the phrase “DO NOT EAT”, and if manageable, insert a specific symbol to indicate the intelligent device on the package. Points that need to be considered in determining the risk associated with the consumption of IP food products are the migration of intelligent substances or their reaction products, toxicological properties of intelligent substances, and interaction of intelligent substances with food matrices (European Food Safety Authority 2009). Thus, to alleviate consumer acceptance towards IP, it is necessary to reduce or deprive any potential risk of food contamination. The advancement in the fields of chemistry, biotechnology, material science, and microelectronics aid in the significant development of novel economic IP solutions.

8 Limitations and Future Perspectives

The integration of IP in food industries has led to significant improvement in food quality, food safety, shelf life and gradually reduces food loss or wastage. However, few major drawbacks of IP systems cannot be ignored and need further investigation to overcome the same. The higher development cost or production cost is one of the main limiting factors for extensive commercialization of IP systems. Secondly, the larger size of the existing intelligent devices or tools to integrate into food packaging is problematic and should be bought into consideration. Apart from these factors, the lack of public awareness or the limited demand in the market regarding the utility of IP systems is a notable factor affecting the growth of such systems in the commercial market. An ideal intelligent device for food packaging should be user-friendly, simple and reproducible, accurate, reliable, non-toxic, eco-friendly, cost-effective relative to the value of the food item, and compatible with printing technology for mass production.

Even though significant innovations have evolved in IP over the past two decades, there is an opportunity for further research and development. Some points to be considered for future works concerning IP systems are:

- The size and operation steps in most intelligent devices are complex. More research is required to minimize the size of the intelligent device and simplify the intelligent system operations.
- Different kinds of active compounds are infused with the packaging systems to attain new functionalities such as antioxidant and antimicrobial activities. Howbeit, the interaction of these active compounds with the package and product still needs thorough investigation. The effect of these extraneous compounds on the nutritional value, cooking properties, and sensory attributes need to be explored in detail.
- Another vital point to be considered is the nontoxicity of materials and packages used for IP systems. The integration of materials for IP should be performed by amending the necessary safety regulations due to the migration ability of few compounds to the food.
- The IP systems are found to be commonly used for a large class of fresh foods like meat, fish, fruits, and vegetables. However, extensive research on the contribution of IP in liquid foods like milk, fruit juices, and other beverages is still minimal.

- Synergistic technology is to be encouraged for ensuring improved quality and safety of foods. Combination of AP and IP help in the creation of smart packaging. The changes which occur inevitably in the packaged food can be managed by AP, and the condition of the product and its environment can be continuously monitored with the help of IP.
- The introduction of multifunctional sensing devices into smartphones and other gadgets is needed to make the IP systems user-friendly and reliable. The monitoring of food products with these devices should not be limited to colour change, but also with origin, authentication, nutritional information, etc.
- Eco-friendly IP comprising of biodegradable materials which can be reused, renewed, recycled, or repurposed should be encouraged for future food packaging production. Extensive work should be conducted to manufacture IP systems that can carry more complex information and reduce packaging waste.

9 Conclusion

Intelligent packages can be considered as communicative packages that help in monitoring, evaluating and informing suppliers, retailers, and consumers about the quality and safety of different food products such as meat, fish, dairy, fruits, and vegetables. The food producers, food processors, logistic operators, retailers, and consumers are the subjects of innovations. Howbeit, the innovative packaging solutions must amend the regulatory requirements and subdue major expenses of such newly developed packaging systems. Technological problems are the primary hurdle in commercializing the IP systems. A multidisciplinary approach involving researchers and industrialists from varied disciplines, including food science, food engineering, microbiology, material science, electronics, and electrochemical engineering, is necessary to successfully design, develop, and implement potential IP systems in the market. Besides, IP and its materials have to be sustainable with regard to design, production, and application. The challenges of environmentally sustainable technology; interest versus reusability, reversibility, and multifunctionality should be overcome. In conclusion, continuous research in the field of food packaging help in reducing the cost and complexity of IP systems and development of novel packaging solutions to enhance the quality, safety, and shelf life of food products.

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