Sustainable Food Technology

ROYAL SOCIETY OF CHEMISTRY

REVIEW

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Cite this: *Sustainable Food Technol.*, 2025, **3**, 161

Received 3rd October 2024
Accepted 4th December 2024

DOI: 10.1039/d4fb00296b

rsc.li/susfoodtech

Recent technological advances in food packaging: sensors, automation, and application

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Around one-third of the food produced globally is wasted, and on the other hand, there are rising concerns about hunger, malnutrition, and food insecurity. Food spoilage may occur without any visible alteration in food's appearance or odor, deceiving the consumer into assuming that the food is safe for consumption and increasing the possibility of contracting food-borne diseases. Intelligent packaging has emerged as a novel packaging system to interact with consumers about the freshness and shelf life of the food, thereby elevating food safety and reducing food wastage. In this review, the recent advances in intelligent packaging systems such as indicators, sensors, and AIDC technology employed to enhance food safety and security are discussed. The authors intend to elucidate the types of intelligent packaging systems and their application in packaging various food products. Additionally, the mechanisms behind the working of intelligent packaging systems are emphasized based on previous literature. Furthermore, this review seeks to highlight the benefits and limitations along with the challenges encountered during the commercialization of intelligent packaging.

Sustainability spotlight

The need for improved food packaging stems from challenges like food spoilage, safety concerns, and food wastage. The conventional packaging contributes to food waste and poses health risks due to contamination and miscommunication. Sustainable advancements include smart packaging systems that employ sensors to detect spoilage, ensuring food quality and safety. This article supports Goal 12 "responsible consumption and production" of the UN's Sustainable Development Goals that ensures sustainability.

1. Introduction

From farm to plate, food products are subjected to contamination by physical, chemical, and biological means.[1] Traditional packaging is a passive system that aims to safeguard the product from a harmful environment necessitating smart systems to extend the benefits of the packaging. The goal of active packaging is to prolong the shelf life and preserve the quality of food while intelligent packaging offers quality recognition and tracking technologies that seamlessly interact with consumers on the freshness, safety, and overall quality of the food.[2] Novel food packaging technologies typically aim to ensure food security by estimating the extent of food spoilage.[3] The quality of food products depends on several intrinsic factors such as moisture, pH, composition, and initial microbial load, and extrinsic factors such as humidity, storage temperature, and external microorganisms.[4] The role of intelligent packaging systems is to sense, detect, monitor, and record the internal and external parameters of the packaged food corresponding to stimuli. The active compounds are integrated into the packaging system to monitor and determine the quality throughout the supply chain and identify the critical points. Intelligent packaging is more precise in giving information about volatile compounds of biogenic amines, toxins, microbial organisms, and their origin. Food quality is traditionally determined based on multiple characteristics such as healthiness, consumer requirements, nutritive advantages, and reliability. Intelligent packaging is being employed to continuously monitor these parameters and their timely indication.[5]

Intelligent packaging systems can be applied to dry solid products such as fruits and vegetables, semi-solid foods such as yogurt and curd, and liquid foods such as beverages. This budding intelligent technology in the packaging sector preserves the integrity of food and informs consumers about packaged food products. This intelligent system potentially augments decision making and evaluation by offering sufficient information on changes in food quality and alerting users to potential hazards. Smart packaging technologies boost awareness about alterations in food inside the package and display multiple warnings of possible dangers in the packaged food quality.[6] Intelligent packaging systems are employed to lower the energy consumed by the cold chain, as well as the quantity of preservatives needed and food wastage.[7] There is ongoing research on producing labels and seals that remain transparent until the box is opened and change its color when opened due to damage or tampering. Despite

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intelligent packaging being employed for identification, recording, and tracking processes, they are currently integrated with active packaging materials to check their effectiveness.[8] The food spoilage is delayed and quality is maintained by the application of nanomaterials. During recent years, intelligent packaging systems have generally been fabricated using chemical dyes and are currently being replaced by natural dyes such as anthocyanins, curcumin, alizarin, and betalain. Biosensors employ transducers to convert the obtained signal into readable data which are integrated with the packaging system. Fig. 1 depicts an overview of the paper offering a visual representation for enhanced understanding.

Former research emphasized the concepts of intelligent packaging and their implementation in the food industry. The chief objective of this review is to bridge the knowledge gap between several types of intelligent packaging systems, mechanisms of action, and applications in the food industry. In addition, the paper explores and assesses contemporary trends in merging diverse ideas and technology with intelligent packaging representing the future of intelligent packaging.

2. Recent advancements in intelligent packaging

The innovative integration of nanotechnology and intelligent packaging leverages nanoscale materials and devices to fabricate smart packaging systems that can monitor, protect, and interact with packaged food. Nanotechnology contributes to sustainable packaging alternatives by lowering the demand for superfluous materials and boosting the recyclability of packaging. Intelligent packaging systems optimize resource utilization and minimize ecological impact throughout the lifecycle of the product. Nanotechnology facilitates the integration of nanobarcodes and other traceable elements at the nanoscale into the packaging material with economic benefits. Despite the numerous benefits offered there are concerns regarding the migration of nanomaterials into the food, questioning the safety and regulatory compliance. There is a need for clear regulatory frameworks to guarantee liable commercialization of nanotechnology in food packaging.[9] Waste material-based intelligent food packaging represents an innovative and sustainable strategy for addressing environmental issues whilst booting the functionality of food packaging. Innovations in waste-based intelligent packaging need to address technical, logistical, and economic concerns to attain widespread acceptance in the food industry. This strategy reduces improper waste management, provides economic value to waste, and minimizes the negative environmental impact of conventional packaging materials. Apart from the advantages, there are challenges related to the safety and regulatory compliance of intelligent packaging derived from waste.[10] 3D printing enables the construction of customizable and intricate

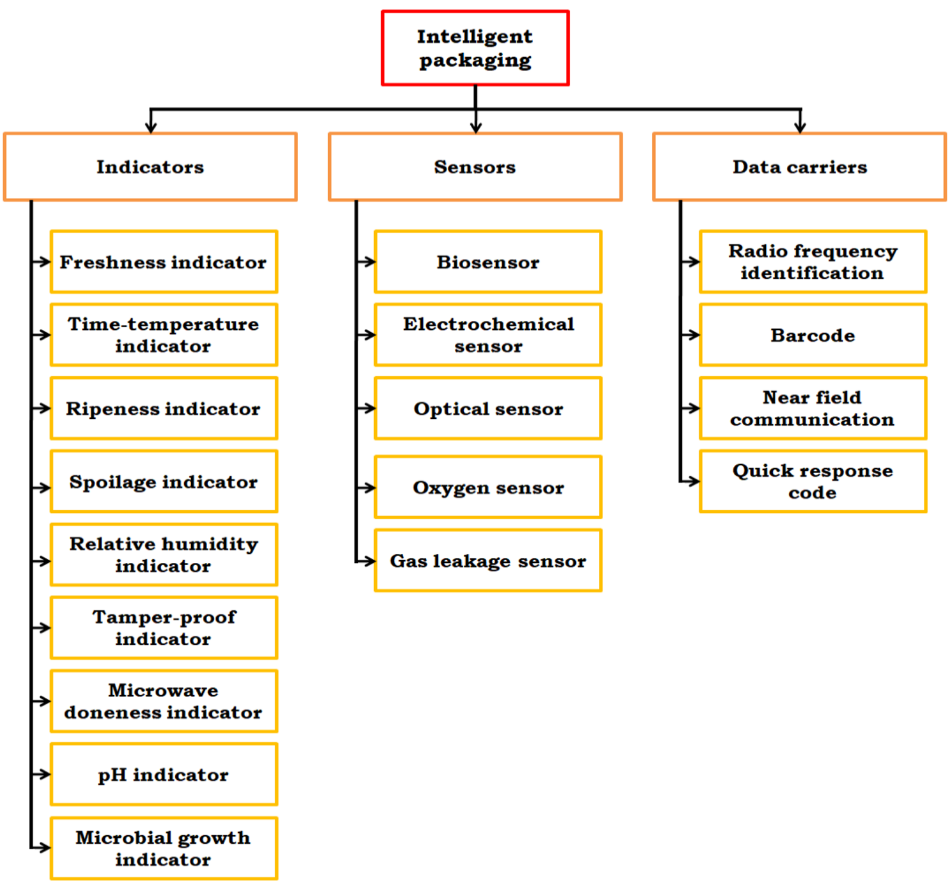

Fig. 1 Classification of intelligent packaging employed in the food industry.

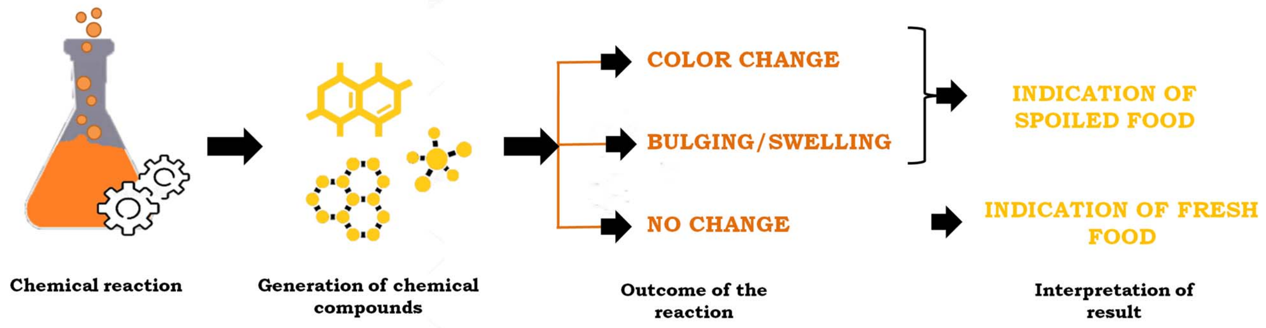

Fig. 2 Overall mechanism of communication by intelligent packaging systems.

food packaging designs and the shapes and sizes of the packaging can be tailored to match specific food products *via* optimizing space utilization to thereby reduce material waste. 3D printing also facilitates rapid prototyping and iterative design processes for sensor-integrated objects. Advanced 3D printing technology supports multi-material printing enabling the incorporation of various materials for sensors and indicator components. The flexibility of 3D printing enables the inclusion of sensor enclosures and indicator compartments directly into the packaging, offering a seamless integration of smart technology. The total cost involved in 3D printing the intelligent parts of packaging remains prohibitively expensive for large-scale applications. The integration of 3D printing technology and intelligent packaging is a significant advancement paving way for new opportunities in intelligent food packaging.[11]

3. Types of intelligent packaging

Intelligent packaging systems are classified into three categories namely indicators, sensors, and radio frequency identification systems. Each of these systems is further classified into subcategories and each one is detailed in the following section.

3.1 Recent advances in indicators

Indicators are a type of intelligent food packaging that offers real-time information, ensures product quality, and augments overall consumer satisfaction. The integration of smart indicators contributes to a more secure and efficient food supply chain. Fig. 2–4 depict the mechanism of action of indicators and sensors. The food that tends to spoil results in the release of volatile compounds, and these volatile compounds are indicated by the indicators that can be seen visibly by color change and other odor-emitting indicators. Some sensors are there that detect the presence and concentration of gases that determine the spoilage of the fruit and vegetables.

3.1.1 Freshness indicators. The freshness indicator determines the real-time quality of foods during production, packaging, and supply chain management for the producers and the consumers.[12] The freshness indicator depends on the spoilage compounds in the foods such as volatile sulfides and amines, and the development of the freshness indicator over the last 2 decades has a high importance. The freshness indicator depends upon the total volatile basic nitrogen content (ammonia gas) produced from the food sample.[13] The silver and copper ions were coated on the thin films and the plastic films of about 1–10 nm, and when the food tends to spoilage release of amine compounds thereby changing the color to dark red.[14] Compounds such as polythiophene in the packaging film are also responsible for the amine compounds and changes in color during tuna fish spoilage.[15] Sensors were developed by Food Quality Sensor International to determine the freshness of the meat products by placing the sensor as a part of the package. E-

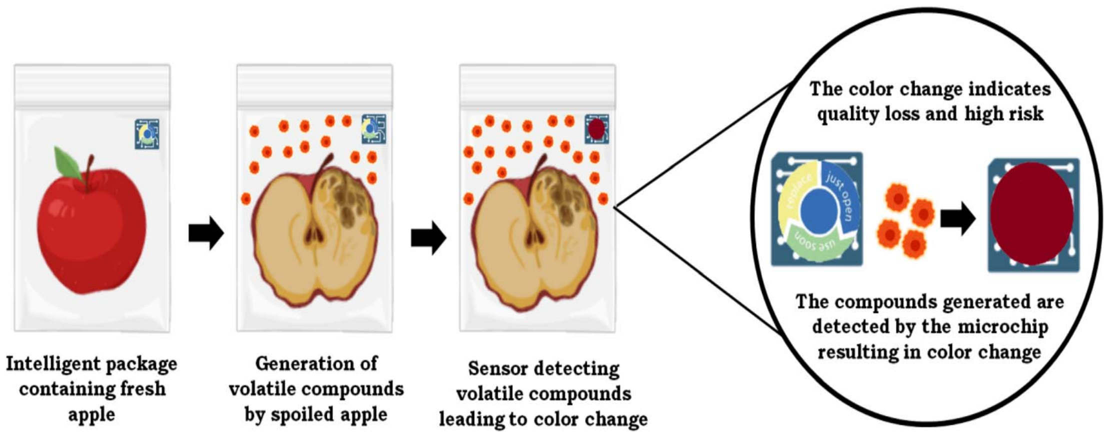

Fig. 3 Spoilage detection mechanism of indicators and sensors.

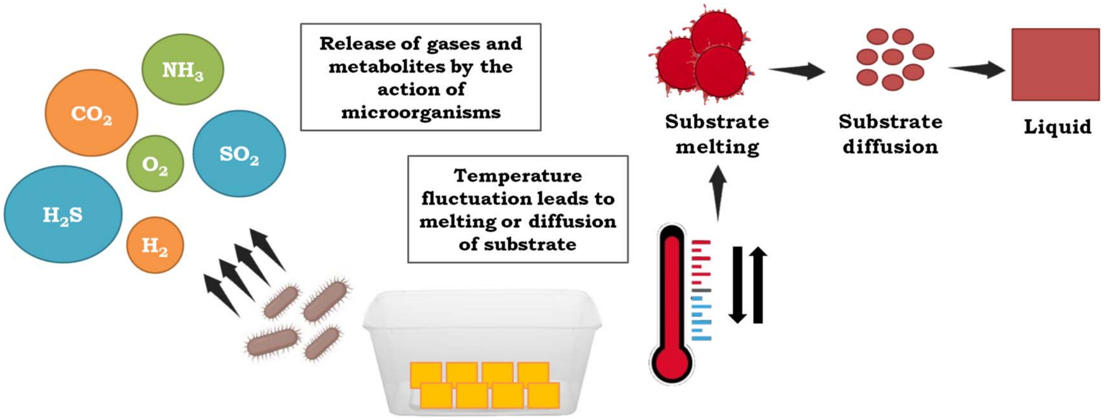

Fig. 4 Mechanism behind color-changing intelligent packaging systems.

noses had been developed for sensing trimethylamine in raw food to determine the freshness of the food.[16] Curcumin, a polyphenolic compound was added to polymeric films containing chitosan, starch, pectin, hydroxypropyl methylcellulose, gelatin, and carrageenan to determine the freshness and quality of the food product by using a responsible color-changing pH sensor. Carbon nanotubes were developed to determine carbon dioxide, amine, and volatile sulfide in the packaged food.[14] Hydrogen sulfide indicators were employed to determine the freshness of meat products based on the mechanism of release of hydrogen sulfide to react with the myoglobin in meat resulting in a color change in the indicator as the meat ages.[13] Researchers developed a fish freshness indicator using cresol red and bromocresol purple in the packaging. A color transition from yellow to black to purple was observed based on ammonia concentration corresponding to spoilage levels. Fish samples were stored at 4 °C, 10 °C, and 20 °C temperatures for seven days, and the indicator reliably monitored spoilage by a non-destructive method to assess fish quality.[17] Nanosensors used in food packaging plants include nanoparticle-based sensors, array biosensors, nanocantilevers, nano-test strips, nanoparticles in solution, and E-noses.[18] A company named "COX Technologies" developed the freshness indicator called "Freshtag" which indicates the freshness of meat and fish products. When the products spoil, there is a release of amine volatile compounds that are responsible for the pink color change. The mechanism behind the working of indicators is to detect the metabolite produced by the spoilage-causing microorganisms resulting in a color change in the system.[19] Some indicators show color change with changing pH, and the release of volatile nitrogen compounds, hydrogen sulfide, and enzyme substrates produced by the microorganisms.[20]

Curcumin along with a chitosan and polyethylene oxide nanofiber film was developed to indicate the freshness of chicken breast packages when stored at 4 °C. The color of the nanofiber film changed from bright yellow to red due to a change in pH from 6.2 (fresh chicken) to 6.7 (spoiled chicken) providing an opportunity to detect loss in freshness by the naked eye of untrained consumers.[21] Cellulose-chitosan films with the addition of carrot anthocyanins demonstrated that they could be used as a food-grade biomaterial to control the freshness and spoilage of milk.[22] A chitosan-based film with anthocyanins derived from Jambolana fruit which shows changes from red to blue when used to monitor the freshness of shrimp stored at temperatures between −20 °C and 20 °C has been developed and analyzed for optical properties, moisture content, solubility, and water contact angle.[23] For freshness, compounds such as bromocresol purple, bromothymol blue, and a mixture of bromothymol blue and methyl red were added to the polymer to determine the quality of the meat. Some of the commercially available freshness indicators are Toxinguard® by Toxin Alert Inc., to determine the growth of *Pseudomonas* sp., and Sensor Q™ by FQSI Inc., to detect the freshness and spoilage in meat and poultry products. An adhesive label "Fresh-Check" was developed to ensure the freshness of perishable food products based on a color change mechanism. As the food begins to spoil, the sample temperature increases, and relative to the temperature the color of the dark circle in the fresh check sensor darkens.[24]

3.1.2 Spoilage indicators. Food packaging employs spoilage indicators to communicate to the customers and retailers when food is no longer safe for consumption to ensure safety *via* visual evidence. These indicators primarily identify the growth of specific microorganisms by reacting with enzymes or secondary metabolites produced by the spoilage-causing microorganisms. For instance, seafood such as pomfret fish and shrimp spoilage have been monitored employing chitosan films enriched with oxidized chitin nanocrystals and black rice bran anthocyanins. The films show a color change from purple to blue-grey after 24 hours of storage due to the increase in the total volatile basic nitrogen in the packaging film.[25] A curcumin-induced bacterial cellulose and potato peel film has been used in pork meat packaging and it interacts with the sample by reducing the monoaldehyde. The addition of curcumin decreases the tensile strength without disturbing its thermal stability. Alginate and polyethylene oxide are applied as functional indicators in packaging to detect the presence or absence of specific compounds at a particular period which in turn determines the spoilage which occurred.[26] Freshness indicators can also be used to determine the spoilage of food products and the quality can be assessed based on chemical composition and microbial composition. The metabolites produced by microorganisms such as diacetyl, amines, carbon dioxide, ammonia gas, and hydrogen sulfide gas react with the components of indicators incorporated in the packaging materials and results in color changes. The spoilage of buffalo meat is determined by a colorimetric-based packaging film with bromophenol blue by sensing volatile nitrogen gas which is stored under refrigerated conditions and has a color changing capacity from yellow to blue. The shelf life of poultry meat, seafood, meat, and cheese can be increased by using alginate-based polymeric films. Another study developed a colorimetric spoilage indicator using polylactic acid nanofibers impregnated with anthocyanins derived from red cabbage to monitor spoilage in beef. The spoilage indicator detected ammonia concentrations as low as 1 ppm identifying bacterial growth thresholds (107 CFU mL^{-1}) in beef after 10 hours at room temperature and 7 days under refrigerated conditions.[27] The nanomaterials can be added to the films as they increase the water barrier capacity and mechanical properties.[28] The shelf life of bananas has been increased by packaging the bananas with agar-based polymeric films with the incorporation of red radish and essential neem oil. The nanoparticles are coated on the surface of the polymeric film to augment the mechanical properties without any deterioration in weight and barrier properties.[29]

3.1.3 Ripeness indicators. Ripeness indicators in food packaging offer consumers a visual indication of the ripeness, readiness, and freshness of the produce for consumption. These indicators help reduce food waste by enabling consumers to choose fruits and vegetables at their ideal ripeness and ensure superior quality. The indicators comprise sensors that respond to specific gases especially ethylene, a plant hormone released by fruits and vegetables, by changing color. The ripeness of apple fruit was studied by fabricating ripeness indicators made up of Ni–SnO_2 incorporated into a thin film.[30] The chemical vapor deposition of manganese oxide and cross-linking with gold and silver possess the ability to determine the degree of ripeness by estimating the ethylene content in fruits and vegetables.[31] Researchers studied the ripeness of the apple fruit by employing an on-package colorimetric sensor designed using polymeric substances and methyl red to detect the aldehydes emitted during ripening. The sensor was designed based on the color change from yellow to orange and red as the end color. A study employed visible-near-infrared spectroscopy to detect alterations in grape quality during ripening. Five berries were randomly picked from each batch using the five-point sampling method. Four batches of grapes were collected in various stages of ripening, with approximately 800 berries in each batch. As the grapes matured, the redness (a*), and Chroma (C*) values were elevated, and soluble solid content, lightness (L*), yellowness (b*), Hue angle (h*), hardness, and total acid content were relatively reduced.[32] The ripeness indicator "RipeSense" was fabricated to determine the quality of apples without human intervention such as touch/smell/taste. The indicator detects the ethylene gas evolved during the ripening process of the apple.[13]

3.1.4 pH indicators. pH indicators are substances that undergo color changes in response to the acidity or alkalinity of their environment. They interact with the food or its surroundings when incorporated in food packaging to offer visual indications regarding the state of the product. The change in the pH level of the food/environment is majorly due to spoilage or chemical reactions, resulting in a color change in the pH indicator. A pH-sensitive chitosan-based film was developed with dyes extracted from the Bauhinia Blakeana Dunn flower. The film has been applied as a sticker sensor on the packaging material to test the freshness and pH changes in fish. The change in pH is due to volatile amines released from the fish during storage which results in a color change from purple to green.[33] The application of a chitosan and polyvinyl alcohol film infused with anthocyanin extracted from red cabbage has been studied as a wrapper for pork belly slices. The film turns yellowish from a pale green color.[34] A similar material prepared with anthocyanins extracted from fruit and sweet potato has been tested on meat samples at three different temperatures −20 °C, 4 °C, and 20 °C for 72 hours. The color change of the film from red to blue occurs over storage time, and it can be concluded that meats stored at 4 °C and 20 °C are said to be contaminated after 72 hours and 24 hours, respectively.[35] The addition of alizarin to the chitosan-based film was conducted and the spoilage in fish was studied depending on a pH change. There is an observed color change in the film from yellow to purple.[36] Black plum peel waste was employed to extract anthocyanin which was incorporated into the chitosan-based films along with titanium oxide nanoparticles indicating spoilage when the pH changed from acidic to basic.[37] The black and purple rice extracts were extracted and incorporated into the chitosan film to determine the pH of the pork samples.[29] Jamun extract incorporated into the polyvinyl alcohol-based film along with nutmeg oil provides the film with a color-changing capacity from violet to red to determine the freshness of the product concerning pH change.[28] In a study, anthocyanins extracted from *Ipomoea coccinea* were treated with polyvinyl alcohol and guar gum to create antioxidant and pH-sensitive films to monitor the freshness of chicken. The film developed with 20% anthocyanin extract exhibited excellent color-changing character and antioxidant activity. Furthermore, the physical properties, such as a thickness of 150.5 ± 17.86 μm were enhanced and water vapor transmission (4.95 ± 0.29 mg day^{-1} cm^{-2}) was reduced indicating the film to be a potential poultry packaging material.[38] Titanium oxide nanoparticles were used as the pH indicator in the developed chitosan films to study the storage of salmon meat.[36] Purple potatoes were used to extract anthocyanin to determine the spoilage of fish in both acid and alkali media.[39] The packaging of prawns was studied by utilizing butterfly pea flower-derived anthocyanin along with an infusion of titanium oxide nanoparticles into the starch-based films.[40]

3.1.5 Time–temperature indicators. Temperature is one of the environmental factors that negatively impact the shelf life of food products. The increase in temperature from the critical point even by 1 °C leads to an increase in water activity, changes in the internal structure, and nutrition loss.[12] Time–temperature indicators (TTIs) inform the consumer if the product was maintained at the required temperature throughout transport and storage. TTIs are small self-adhesive readily available indicators that are user-friendly and information is readily communicated to the consumers for them to choose between purchasing the product based on the quality. TTIs record the temperature history of the product over the stipulated period, especially during the transportation of perishable and frozen food products.[2] TTIs monitor food freshness by responding to alterations in physical, chemical, or biological characteristics. For instance, physical TTIs rely on modifications such as melting or structural deformation due to time/temperature variations; chemical TTIs detect reactions like pH change, polymerization, and acid–base reactions; and biological TTIs track the biological activities, such as the growth of spores and microorganisms, indicating the quality of food over time.[41]

The working principle and application of time–temperature indicators are elaborated in Table 1. TTIs possessing market applications are Monitor Mark™ by 3M (USA), Fresh-Check® by Lifelines Technologies Inc. (USA), CoolVu™, OnVu™ by Freshpoint (Switzerland), Checkpoint® by Vitsab International AB (Sweden), Tempix® by Tempix AB (Sweden), Timestrip® by Timestrip Plc (UK), and Smartpak® by Trigon Smartpak Ltd (UK).[42] For instance, "Timestrip UK Private Limited" designed a TTI named "Timestrip" in the form of a label to determine and record the temperature over some time and indicate when the temperature has changed to a level below/above the acceptable level. The fabricated indicators have been successfully employed in monitoring fresh seafood, airline catering, school meals, home delivery diets, and food retailing. TTIs have also been applied in food processing industries to monitor and assess the pasteurization and sterilization processes of milk. The processing conditions and spoilage parameters can be assessed by using these indicators. The chitosan-gold nanoparticle combination was employed to develop a composite that indicates the frozen state and thermal history of food based on the visual change that accompanies the agglomeration of gold nanoparticles due to their localized surface plasmon resonance.[42]

The heating and freezing temperature of the meat and meat products can be determined by this sensor.[48] Laccase was immobilized on electrospun chitosan fibers to fabricate TTIs for food quality monitoring. Laccases, primarily catalyzing the oxidation of phenolic compounds such as aminophenols, polyphenols, and phenols, can oxidize guaiacol with visual and color changes from transparent to deep brown or deep purple-brown during fluctuation of temperature.[43] TTIs were fabricated employing lactic acid as the major compound and a substrate at different concentrations which was associated with color changes based on the diffusion of lactic acid. The vapor diffusion of lactic acid results in an irreversible color change of a chemical chromatic indicator from green to red that progressively occurs due to pH reduction.[47] Lipase derived from *Burkholderia cepacia*, *Aspergillus niger*,*Weissella cibaria*, and lactic acid bacteria was loaded with a calcium alginate microparticle and glycerol tributyrate combination for detecting the quality of ground meat, beef, and fish over time,based on temperature using TTIs. Silver nanoparticles have been widely employed in fabricating TTIs and enable the integration with packaging films.[46] The silver nanoparticles are responsible for the color change due to the increase/decrease in temperature from the critical point. The color of the TTI changes to blue by the action of temperature rise/drop and the color intensity depends on the extent of temperature deviation.[49] The combination of silver nitrate with reducing agents such as ascorbic acid facilitates the silver atoms to get deposited as ions on the film, and as the temperature deviates there are changes in the

Table 1 Mechanism of time–temperature indicators and their application in the food industry

Type of TTI	Mechanism of operation	Food products	Application in food packaging
Color-changing TTI	Chemical reaction causing a color change	Meat products-fish	Indicating cumulative temperature exposure over time[12]
Enzymatic TTI	Enzymatic reactions	Beef products	Reflecting the duration and severity of temperature exposure[43]
Microbial TTI	Microbial activity	Quail eggs	Indicating temperature abuse and potential spoilage[29]
Diffusion-based TTI	Rate of diffusion of a substance	Milk powder, coffee, and tea powder	Reflecting temperature history and potential quality degradation[29]
Melting point indicators	Melting of a specific substance	Mango and papaya	Showing cumulative temperature exposure and potential issues[44]
Electrochemical TTI	Electrochemical reactions	Food products	Indicating temperature fluctuations and duration of exposure[44]
Radio-frequency identification tags with TTIs	Electronic monitoring	Tomato	Providing real-time temperature data through RFID technology[45]
Thermochromic labels	Color change at specific temperatures	Milk	Indicating exposure to temperature conditions beyond a threshold[46]
Bimetallic TTI	Expansion of metal alloys	Ice creams	Reflecting temperature exposure over time and potential issues[47]
Phase change materials (PCMs)	Change in the physical state	Meat products	Indicating temperature variations and cumulative exposure[43]

kinetics leading to a color transition from red to yellow and green.[12] Another example is when researchers studied the application of anthocyanin extracted from red cabbage incorporated in the film developed with chitosan and polyvinyl alcohol to detect the spoilage of milk. The milk spoils with temperature deviation over time resulting in a color change of the TTI.[50]

3.1.6 Microbial growth indicators. Nanomaterials such as quantum dots have been employed to detect bacterial growth as they are conjugated with the microbes, and the quantity of quantum dots depends upon the fluorescence, decay time, stability, and sensitivity. Cadmium selenide/zinc sulfide quantum dots were used to determine microbial growth as they turned into a fluorescent blue color.[51] Quantum dots are considered a type of down-conversion phosphors as they provide higher energy radiation whereas the up-conversion fluorescence system produces low energy necessary for detecting carbohydrates, proteins, enzymes, vitamins, carbon dioxide, minerals, bacteria, and DNA.[52] Based on this principle of biomolecule up-conversion conjugates, a test kit was developed to detect the presence of *E. coli*.[53] Apart from quantum dots, several materials have been employed to identify microbial deterioration. A sensitive chitosan-Bauhinia blakeana Dunn film was successfully developed to detect contamination in pork meals based on color changes in the packaging film from brown to green. It was observed that after 48 h, there was color change, indicating an obvious pH change in the sample.[37] Research has been carried out for identifying microbial spoilage in pasteurized milk that turns from grey to dark pink when the milk is contaminated. The anthocyanins derived from red cabbage are incorporated into the chitosan-based intelligent packaging resulting in a color change when the milk reaches a pH value of 4.6 due to exposure to temperatures above refrigeration temperature for time intervals ranging from 0–4 days.[30] The quality of chicken thigh meat was measured based on the level of microbial spoilage by employing bacterial cellulose-polypyrrole-zinc oxide nanoparticle-infused packaging films. The zinc oxide nanoparticles possess the capacity to evaluate microbial spoilage, and chemical characteristics, particularly the pH of food, and hence identify the quality of the food.[54] To monitor the freshness of fish and poultry meat, a composite intelligent food packaging film was fabricated using polyvinyl alcohol and gelatin combined with amaranthus leaf extract (ALE) due to its high betalain content and antioxidant activity. The presence of betalains in ALE changed the color of the film when exposed to basic pH. The film incorporated with ALE demonstrated improved UV light protection, decreased water solubility and vapor permeability, and improved mechanical characteristics.[36]

3.1.7 Relative humidity indicators. Moisture determines the rate of microbial growth; however the rate of microbial growth in low-moisture food accelerates with higher humidity creating a need for a humidity sensor that aids in maintaining humidity levels.[54] Iridescent films are being developed to indicate the humidity level based on color changes due to interaction with the electromagnetic field used in the humidity sensor attached to the developed packaging film.[12] The concept of a photonic crystal hydrogel involving coatings on lateral spheres of poly(styrene methyl methacrylate acrylic acid) with photopolymerized acrylamide has been used to develop a humidity sensor.[55] Wheat gluten protein was studied as an ingredient for monitoring relative humidity. The interaction between different phases of water and wheat gluten has been investigated at low, medium, and high hydration levels, with the percentage of paired and free water molecules present that determined the material reaction.[53] With the use of styrene and methacrylic acid monomers combined by radial copolymerization, different colors can be attained depending on the moisture percentage.[56] Humidity sensors have been developed from chitosan and $CuMn_2O_4$-spinel nanopowder based on the impedance change. With increasing humidity, the impedance of the sensor decreases and can be attributed to charge carrier generation under the effect of temperature.[57] Zinc oxide nanoparticles owing to their electrical impedance along with the glycerol and gelatin-contained packaging films were employed to measure the relative humidity at room temperature. Humidity sensors based on quartz crystal microbalance coated with chitosan-multiwalled carbon nanotubes have been developed. The optimized sensor possesses high response sensitivity, negligible humidity hysteresis, quick response and recovery time, and excellent reversibility, repeatability, long-term stability, and selectivity.[37] Other humidity sensors are based on chitosan-zinc oxide and single-walled carbon nanotubes. In this case, the sensing mechanism is attributed to the swelling effect of chitosan surrounding the nanotubes that changes the hopping conduction path between nanotubes.[58]

3.1.8 Tamper proof indicators. Tamper-proof indicators are used to detect leaks and opening of the package before being delivered to the consumers. Tamper-proof indicators also leave irreversible, visible evidence that serves as proof of whether the label has been tampered with ensuring the safety and integrity of the package. They work by detecting the oxygen and carbon dioxide concentration as well as color changes depending on the enzymatic and chemical reactions.[20] Tamper-proof seals are usually employed in perishable products such as milk and yogurt to ensure that the contents were not accessed or contaminated after packaging as dairy products are highly susceptible to microbial contamination. Tamper-proof indicators are necessary for bottled packaging such as bottled water, carbonated beverages, and alcoholic drinks as evidence that the content inside is safe. Tamper-proof indicators in canned foods such as soups, sauces, and canned vegetables are necessary to ensure that the contents are preserved correctly and are not exposed to contamination.[58] A combination of zinc oxide nanoparticles, grape seed extract, and cellulose nanocomposites has been employed to fabricate vapor-proof packaging. The addition of halloysite-nano clay with potato starch nanoparticles offers moisture barrier and vapor barrier properties.[59] Cellulose-based starch from banana peel and titanium dioxide nanoparticles were utilized to produce a film for light tamper application. The concentration of the titanium oxide was directly proportional to the hydrophobicity of the film while the increase in starch concentration resulted in the augmentation of mechanical and tamper properties.[60]

3.1.9 Microwave doneness indicators. "Doneness" indicators are packaging techniques that indicate convenience, quality, and temperature. They detect and indicate the ready stage of heated meals that are often employed in ready-to-serve foods. In poultry products, "ready" button indications are often used. When a specific temperature is achieved, the material expands and the button pops out, informing the user.[61] Microwave indicators play an important role during the thawing of ready-to-eat frozen foods such as popcorn, pizza, and sandwiches and the cooking of half-cooked foods such as chicken strips, sausage, and bacon. The mechanism of doneness indicators is similar to that of thermochromic ink which is that a colour change occurrs as the temperature of the product increases. Conductive inks can also be employed to indicate doneness. As the food reaches the desired temperature, the change in resistance activates the circuit, causing it to emit light. Alternatively, heat-sensitive labels that change color when the desired temperature is achieved may be affixed to the food packaging, clearly indicating the doneness level. The limitation of the microwave doneness indicator is the difficulty in determining the point at which the color changes. The observation of color change during microwave heating when the oven is closed is complicated.[62] Indicators depict changes *via* visual responses, especially changes in color. This color change is often triggered by mechanisms such as the melting of a substrate in the packaging coating when exposed to varying temperatures and the release of gases and chemical constituents from food, or due to microbial growth. Moreover, indicators also respond to changes in humidity, pH levels, or the presence of spoilage compounds to monitor food quality and safety. Their integration into packaging systems helps provide real-time information about the product's condition and reduce food waste.

3.2 Recent advances in sensors

Sensors are devices designed to monitor various parameters, detect anomalies, and provide real-time data by responding to improve decision-making. Sensors are classified further as discussed in the following section.

3.2.1 Biosensors. Sensors are used for detecting, locating, recording, and quantifying energy and transmitting the electronic signals to the readable scale and they also have a bioreceptor and a transducer to analyze the analyte and transmit the signals. Biosensors are a promising and innovative technology for future intelligent packaging systems and it has various applications as it measures the physical and chemical parameters of the food. The prime components in the biosensors include biological compounds such as enzymes, antibodies, antigens, phages, and nucleic acids. These biosensors can detect parameters like light, pH, temperature, mechanical force, electric field, metabolites, or solvent composition by utilizing the hydrophilic and hydrophobic states of the materials.[63] Biosensors are similar to chemical sensors yet are discrete in detecting different biological compounds such as cells, antibodies, bacteria, yeast, fungi, plant and animal cells, biological tissue, or enzymes. Biosensors also possess the ability to detect volatile compounds, gas molecules, and chemical substances with higher selectivity and sensitivity such as H_2, CO, NO_2, O_2, H_2S, NH_3, CO_2, and CH_4. The most successful biosensors are the glucose sensors in the healthcare department that can be even used in food, pharmaceuticals, environment, military, and other safety-critical sectors. The commercially available biosensors include Ageless EyeTM, Shelf-Life Guard, Tell-Tab, and Tufflex GS.[64] The biosensor named "Toxin GuardTM" was employed to detect pathogens and microorganisms such as *Campylobacter* sp,*E. coli*,*Listeria* sp, and *Salmonella* sp. present in muscle-based food products and in some fruits and vegetables. The spoilage bacteria bound to the antibody in the film results in color changes indicating quality loss.[42] The Flex Alert company developed a biosensor for the detection of pathogens such as *E. coli*,*Salmonella,* and aflatoxin in coffee beans, dried nuts, seeds, wine barrels, and fresh fruit that has been commercialized.[65]

3.2.2 Chemical sensors. Chemical sensors are similar to traditional sensors but differ in their working principle. Chemical sensors are categorized into optical and electrochemical sensors which are detailed in the following sections. The mechanism of action and application of chemical sensors in food packaging are presented in Table 2.

3.2.2.1 Optical sensors. Optical sensors are intelligent indicators that provide information on temperature, gas leakage, color, microbiological spoilage, freshness, carbon dioxide, and oxygen levels.[13] The time–temperature digital indicators are optical sensors that determine the temperature of the product at different time intervals thereby assessing the quality of the product.[69] A digitalized oxygen indicator is also a classification of optical sensors that determines the leakage of the packages, especially MAP packaging.[72] An optical sensor called "Bioett" was developed by Sweden to determine the temperature of the product and a flex alert optical sensor from Canada was used to detect the toxins present in food products. An electronic nose is an analytical tool composed of an array of optical sensors that respond to volatile compounds by changing their electrical properties.[73] The response of the electronic nose is consistent with microbiological analysis and volatile concentration determination of the product.[74] Some of the commercially available optical sensors including Fresh Tag®, Sensor QTM, Food SentinelSystem, and Toxin Guard® are employed to determine the characteristics of vegetables.[75] Single-response optical sensors are the most common technique employed and are nevertheless influenced by several parameters including varied experimental conditions, and the substrate form resulting in a compromise in their accuracy and sensitivity. Therefore, dual-mode optical sensors utilizing independent signals that reduce interference and data instability in complex food matrices are being developed. The independent signals enable mutual verification of signals thus augmenting the accuracy and reliability of the obtained data.[76]

3.2.2.2 Electrochemical sensors. Electrochemical sensors in food packaging operate by leveraging the specific interactions between the sensor's electrodes and target analytes in the food, producing a measurable electrical signal that can be interpreted for quality and safety assessment. Potentiometric, voltammetric, and conductivity measurements are the most popular

Table 2 Chemical sensors and their application in food packaging

Chemical sensor	Targeted compounds detected	Application in food packaging	Food products
pH sensors	pH variation	Monitoring acidity or alkalinity of food products	Tomato[49]
Conductivity sensors	Ion concentration (*e.g.*, salt)	Detecting changes in ion concentration related to spoilage	Meat products[59]
Taste and odor sensors	Various taste and odor compounds	Ensuring the absence of undesirable tastes or odors in food	Milk[66]
Enzyme-based sensors	Specific enzymes or enzymatic reactions	Detecting specific compounds related to spoilage or freshness	Cheese[67]
Biosensors	Biological molecules or reactions	Monitoring specific biomarkers or contaminants in food	Guava[65]
Electrochemical sensors	Various chemicals including gases	Detecting specific gases or volatile compounds related to quality	Canned products[68]
Optical sensors	Light absorption or emission properties	Identifying changes in color or fluorescence associated with spoilage	Meat products[69]
Specific gas sensors	Targeted gases (*e.g.*, ammonia and ethylene)	Monitoring gases related to spoilage or ripening processes	Chicken[70]
Metal oxide sensors	Interaction with specific gases	Detecting volatile compounds associated with food quality	Packed foods[50]
Moisture sensors	Water content	Monitoring and controlling moisture levels in packaged food	Meat products[71]

methods applied in electrochemical sensors.[77] The prime objectives of electrochemical sensors are monitoring oxygen levels, detecting pH fluctuations, and identifying particular chemical components linked to food safety or quality and are especially employed in meat and dairy industries. The electrochemical process takes place at an electrode constructed with a substance which permits easier interaction with the analyte of interest. The working electrode is coated or modified with components, such as gases, ions, or particular chemicals that preferentially interact with the target analyte contained in food. The analyte is involved in a redox process as a result of the contact with the working electrode. This redox reaction produces an electrical current or voltage that is proportionate to the analyte concentration.[44] Electrochemical sensors are widely employed in quantifying colors in food products. In one such study, an electrochemical sensor was fabricated using a modified glassy carbon electrode with graphite flakes for detecting sunset yellow in beverages. The functional groups of electroreduced graphene oxide considerably enhanced the electrode surface activity resulting in an excellent sensitivity, detecting sunset yellow at an extremely low concentration of 19.2 nM.[78]

3.2.3 Oxygen sensors. The oxygen available inside the packaging has an effect on the product characteristics and shelf life. Although modified atmospheric packaging (MAP) and controlled atmospheric packaging (CAP) are frequently employed to mitigate the detrimental impact of oxygen, it does not disclose the quality or degree of spoilage based on oxygen levels, which is now feasible with the implementation of oxygen sensors.[12] Oxygen sensors are integrated with MAP and CAP techniques to determine the presence of oxygen inside the package. Oxygen sensors contain elements such as redox dye, alkaline compounds, reducing compounds, solvents, and bulking agents and are capable of being applied in the format of a label, tablet, printed layer, and coating with a polymeric membrane.[3] A colorimetric oxygen sensor that is irreversible, reusable, and UV-light activated has been developed that could be coated or printed subsequently onto a variety of substrates to produce a blue oxygen sensor film which when activated by UV light becomes colorless. Generally, the nanoparticles and the films are activated by UV radiation to prevent premature oxidation and color change. The "intelligent ink" oxygen sensors comprise a UV-absorbing semiconductor made of TiO_2, methylene blue, a redox indicator, triethanolamine, a sacrificial electron donor, and hydroxyethyl cellulose, an encapsulating polymer. The ink is activated when exposed to UV light inducing methylene blue to reoxidize back to its original blue. The film remains colorless unless, or until, exposed to oxygen, at which point the reduced form.[79]

Titanium oxide along with silver particles, methylene blue hydroxyl ethylcellulose, and glycerol functions as an oxygen sensor by determining the oxygen content, and the intensity is further increased by irradiation with UV light. The titanium oxide nanoparticles are activated by UV radiation which releases electrons from the valence band to the conduction band indicating the oxygen level by the visual change.[80] Another UV-accelerated oxygen sensor was fabricated utilizing graphene oxide as an indicating element. The mechanism of action is based on the photochemical action between the electron acceptors and donors attached to the films by coating or encapsulation.[81] Methylene blue indicators are typically employed as oxygen sensors as methylene blue dye comes into contact with oxygen and is responsible for the transfer of electrons from the valence band to the conduction band due to excitation. After the electrons reach the excitation state, the oxygen sensors get activated and change to their original blue color. The intensity of color change depends on the presence of oxygen in a closed atmosphere.[82]

Table 3 Details of the mechanism of action and application of gas sensors

Type of gas sensor	Gas detected	Application in food packaging
Carbon dioxide gas sensor	CO_2	Monitoring and controlling modified atmosphere packaging (MAP)[83]
Oxygen gas sensor	O_2	Monitoring and controlling MAP to prevent oxidation and spoilage[3]
Ethylene gas sensor	Ethylene	Monitoring fruit ripening and preventing premature spoilage[9]
Volatile organic compound sensor	Various volatile organic compounds	Detecting off-flavors or contaminants in packaged food[84]
Ammonia gas sensor	NH_3	Monitoring for leaks or spoilage in meat and seafood packaging[85]
Sulfur dioxide gas sensor	SO_2	Detecting spoilage and preventing the growth of spoilage organisms[81]
Hydrogen sulfide gas sensor	H_2S	Detecting spoilage and ensuring the quality of packaged products[86]

3.2.4 Gas leakage sensors. The gas leakage sensors should be water-insoluble and non-toxic with the ability to detect gas leakage in the packaging. The gas leakage sensors work based on the mechanism of color sensing possessing a fluorescence color change and an alarm.[62] The commonly employed gas leakage sensors are metal oxides that detect gases such as CO_2, NH_3, H_2S, and H_2O, and also dimethylamine and trimethylamine that are responsible for food spoilage. Gas leakage sensors have been commercialized for industrial applications which include Ageless Eye™ by Mitsubishi Gas Chemical Co., Shelf Life Guard by UPM, Vitalon® by Toagosei Chemical Inc., Tufflex GS by Sealed Air Ltd., and Freshilizer by Toppan Printing Co.[83] Sensors offer advanced mechanisms for detecting food quality, through several techniques which includes chemical responses, gas detection, electrical signal generation, and light-based analysis. Sensors also analyze parameters such as temperature variations and radiation to ensure precise monitoring of food safety and quality. Moreover, sensors are being integrated with advanced technologies such as biosensors, nanotechnology, and IoT for real-time food quality assessment, and shelf-life prediction. These systems play an essential role in tracking freshness, spoilage, and contamination in food products. Table 3 describes in detail the application of gas sensors in food packaging.

3.3 Recent advances in automatic identification and data collection technology

Automatic identification and data collection (AIDC) refers to a group of technologies that are used to automatically identify commodities, acquire information about them, and input that data directly into computer systems without requiring human involvement. AIDC technologies are widely used in various sectors of food such as manufacturing, logistics, and retail to improve data collection efficiency, accuracy, and speed. Fig. 5 presents the application of various AIDC tools in the food industry. AIDC provides advantages such as higher accuracy, better efficiency, lowered human error, and improved data visibility across the whole supply chain. The application of AIDC technology in the food industry is depicted in Fig. 6.

3.3.1 Radio frequency identification systems. Radio Frequency Identification (RFID) systems are tags or chips that determine the real-time data on temperature, relative humidity, shelf life, and nutritional information through a reader by the sender and are useful in production, packaging, and supply chain management.[13] RFID uses tags affixed to food products and raw materials to transmit accurate, real-time information to a user's system. RFID is one of the many AIDC technologies that offer several potential benefits throughout production, distribution, and the supply chain. RFID data are often shared among retailers and distributors to assist in collaborative planning and avoid false rejection of goods by retailers.[87] RFID in the retail industry can improve shipping, receiving, and put-away processes corresponding to suppliers, distribution centers, and retailers. RFID improves traceability by giving specific information on the movement of products. This is especially beneficial in the case of recalls, as industries can immediately track the origin and distribution of affected products, reducing the detrimental effect on customers and the supply chain.[88]

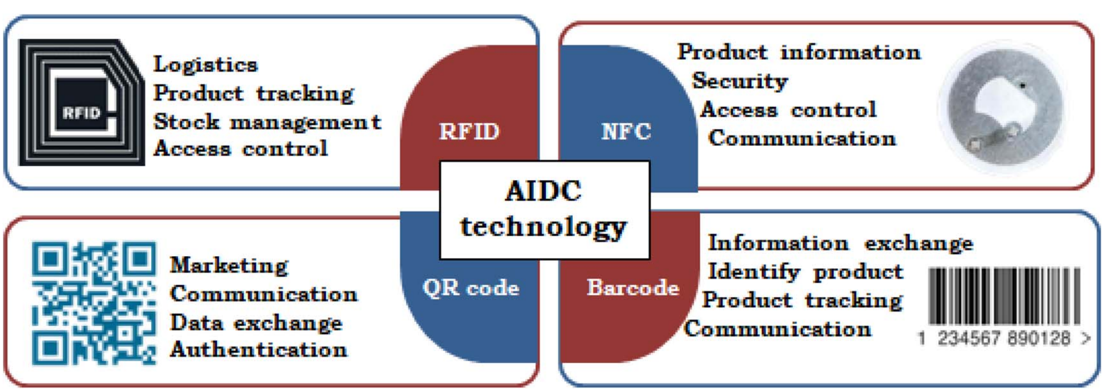

Fig. 5 Application of AIDC tools in the food industry.

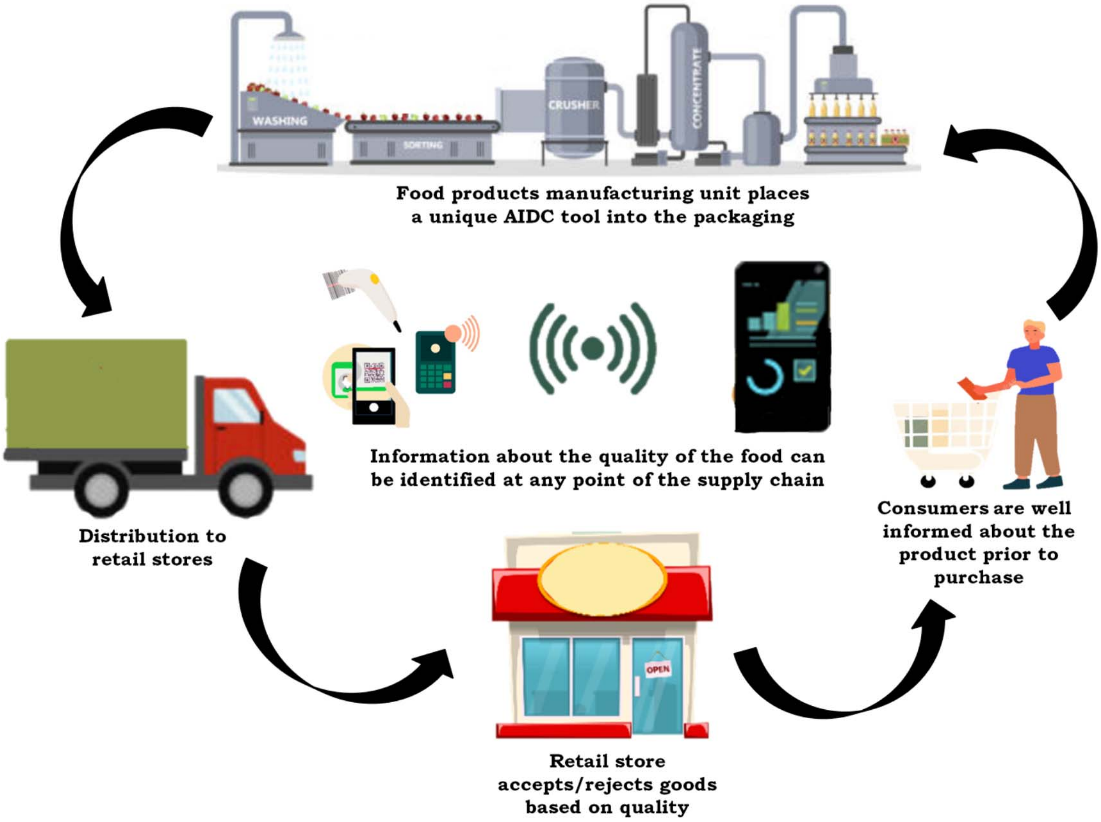

Fig. 6 Application of AIDC technology in various stages of the supply chain.

RFID is not considered intelligent packaging but rather functions as an intelligent component in packaging by communicating product information *via* digital signals.[87] The components of the RFID sensor include the reader, recording unit, and a tag, and works as a whole on the principle of sending and receiving electromagnetic signals.[45] Easy2log®, Intelligent Box, and Temptrip are the commercially employed RFID tags in the food industry.[13] The RFID tag tracks and monitors the real-time quality of food products and offers traceability of location, time, and temperature fluctuations for the food product requiring cold chain application. The advantages of RFID over other data carriers include the storage of large data (1 MB), swift communication, and easy transferring of signals to longer distances (100 m) thereby augmenting the traceability potential. Apart from traceability, researchers have developed an RFID tag capable of offering insights into the freshness of fish by monitoring temperature, hydrogen sulfide, and ammonia gas concentration upon scanning.[89] Currently, nanoparticles and nanomaterials are being experimented with in RFID sensors, barcode tags, and other nanosensors for communication and quality.[26] There is an escalating challenge of managing electronic waste generated and this has stimulated researchers to fabricate "Green RFID devices". Among these, biodegradable RFID tags are manufactured from materials such as paper and wood that degrade swiftly in the environment, while the edible RFID tags are designed to be completely absorbed during digestion, providing novel solutions for both environmental and health-focused applications (Mostaccio, 2023).[90]

3.3.2 **Barcode scanners.** The first universal product code developed was barcode, a low-cost and easily available code that can be widely employed in large retail stores for manufacturers to monitor stocking, reordering, and dispatch throughout the supply chain. 1D barcode comprises parallel lines with equal spacing that represent the data. 1D barcodes are basic technology employed for encoding food information and are seamlessly integrated with multiple software systems within the food packaging sector (Li, 2024).[13] Later, a 2D barcode consisting of dots was introduced to widen the data storage in a smaller area.[91] The use of bar codes in intelligent food packaging materials is currently being investigated. For instance, photosensitive printing inks have been created as pH indicators on bar codes where the intensity of one or more parallel black lines either inceases or drops when the pH changes which can then be read using a bar code scanner for the detection of meat products and milk-based products.[92] The barcode becomes unreadable when a particular microorganism is present.[93]

3.3.3 **Advanced QR codes.** A quick response code (QR code) is a system devised to store information on a bi-dimensional barcode matrix of dots. Despite the lower utilization of QR codes in the food industry, they are progressively being employed in food packaging. QR codes offer consumers every detail about the food, including the nutritional composition, potential after-effects on health, and the existence of

Table 4 Details of recent patents in the field of intelligent food packaging systems

S. no	Invention title	Specifications	Major claims
1	Enhanced RFID-based supermarket assistance system for visually impaired people	The RFID-based supermarket assistance system empowers visually impaired individuals to navigate through supermarkets independently. This is achieved by using advanced text-to-speech and voice interaction technologies. The system utilizes a handheld RFID reader, which retrieves the stored data from the tags and transmits it to the microcontroller for processing and user feedback	Handheld RFID reader, voice recognition feature, access to visually impaired users, eliminate the need for manual assistance, and low power consumption technology[100]
2	IoT-based food spoilage	The designed microcontroller processes data collected from multiple sensors, enabling real-time analysis. An impedance analyzer is integrated to measure the impedance of food following which the quality is evaluated	Transmit stored data, predict future food quality trends, rechargeable battery, and ensuring data integrity in case of power loss[101]
3	A process for developing smart biodegradable antimicrobial films for food packaging with enhanced pathogen protection and shelf-life extension	Arachisan-capped zirconium nanoparticles (ArZrNPs) were synthesized and incorporated into biodegradable food packaging films. The films exhibited excellent antioxidant activity and biodegradability. This packaging is ideal for moisture-sensitive food packaging applications	Synthesized nanoparticles serve as a capping agent, and exhibit antimicrobial and antioxidant properties, and biodegradability[102]
4	RFID-based feasible food calorie monitoring system	The health and dietary management system leverages IoT-enabled technology for efficient dietary monitoring. The device is designed to simultaneously monitor food calorie content and environmental parameters, promoting convenient daily nutritional tracking for users. It employs RFID technology to record food consumption and offers nutritional insights	Diet tracking RFID, real-time interaction with nutritional values, and display calories on a web platform[103]
5	Handheld food item transfer assistive device	The handheld assistive device was designed for automated transport of food from one location to another without requiring any human intervention and thereby ensures food safety. It incorporates a detection system to identify food spoilage and notify the consumer	Detects food spoilage, alerts consumers about potential health issues and maintains hygiene throughout the supply chain[104]
6	A self-healing food packet system	The self-healing food package improves the integrity of frozen foods during transportation. If any one of the layers of the packaging gets damaged, the unique interaction between the layers comprising sodium alginate and chitosan leads to reversible cross-linking. This reaction enables reformation of the layer, allowing the hydrogel to heal itself	Safe transportation of frozen foods, biodegradable polymers, and an antimicrobial barrier[105]
7	Block-chain enhanced food traceability and allergy detection system	The system identifies potential allergens based on user profiles. The system also records and verifies data and prevents the alteration of	Identify potential allergens and analyze ingredient lists, delivering personalized alerts to consumers

Table 4 (*Contd.*)

S. no	Invention title	Specifications	Major claims
		food product information across the supply chain enhancing the safety and transparency	and well informed dietary choices[106]
8	Food-container packing assistive device	The device features a main body equipped with motorized wheels for mobility. A plate on the body allows users to place multiple food containers. This system ensures transportation of multiple packaged food products	Input voice commands for activating or deactivating, and easy transportation of food products[107]
9	Advanced automated storage and retrieval system with autonomous guided vehicle and RFID integration	The component of the Automated Storage and Retrieval System (ASRS) incorporates an Autonomous Guided Vehicle (AGV) equipped with planetary motors and RFID-based navigation for precise movement and package verification	Accurate package retrieval from multiple levels, transport within the storage unit, and real-time feedback to prevent collisions and ensure uninterrupted operation[108]
10	A colorimetric food sensor for identification of freshness of meat and fish	The sensor identifies the freshness of meat and fish by detecting spoilage. The sensor utilizes genipin, a compound derived from *Gardenia jasminoides* (geniposide), to detect spoilage and the emission of biogenic amines, indicators of meat, and fish breakdown without requiring unpacking or direct smelling	Identification of freshness of meat and fish products and color change that correlates with the concentration of the biogenic amines, and maintains functionality and accuracy under various environmental conditions[109]

allergens.[94] QR codes are applied to maintain the level at Critical Control Points (CCP) for facilitating food traceability in case of recall. QR codes are employed to communicate significant data regarding food traceability both forward and backward contributing to augmented food safety in accordance with standards. This provides more clarity to consumers about a food product regarding the contents, source, and manufacture. The scanning and storing of data related to food intake and quantity from QR codes on portable electronic devices assists in the investigation of food consumption patterns.[95] Furthermore, QR codes serve as a powerful marketing strategy to attract consumers and raise awareness about new product launches. For instance, the Coca-Cola Company smartly attached QR codes on packaging to guide consumers to an augmented reality page, enabling them to try on face filters and share them with friends. This innovative approach has proven to be an effective campaign strategy for promoting the brand.[96]

3.3.4 Near field communication. Near-field communication (NFC) provides the benefit of employing wirelessly driven sensors that communicate *via* inductive coupling. The NFC-attached tags and labels potentially assist in preventing the consumption of deteriorated food by informing the buyer or food supplier.[97] NFC is frequently regarded as an extension of near-field RFID. Nevertheless, contrary to RFID, NFC-equipped devices interact among them; otherwise one NFC device operates as an RFID while another serves as a reader. NFC sensors are often embedded into packages to detect and document temperature variations during perishable products' transit and storage. The NFC sensors validate that food is preserved in ideal environments to retain integrity.[98] NFC safeguards digital certifications, quality assurance documentation, and food product compliance data enabling quick retrieval of data. NFC tags lower the possibility of counterfeit products and assure adherence to regulatory requirements. Individuals and organizations throughout the supply chain benefit from traceability, real-time evaluation, and improved interaction by employing NFC tags in food quality management systems.[99] AIDC technology is necessary to augment communication among consumers and retailers, throughout the supply chain. AIDC offers real-time insights into the quality, integrity, and shelf-life of food products. Additionally, AIDC ensures transparency and traceability, facilitates better decision-making, reduces food waste, and authenticates compliance with food safety regulations. Table 4 offers an overview of recent patents filed in the field of intelligent food systems in the food sector.

4. Limitations and challenges

The foremost limitation of integrating electronic devices into packaging in the long term is the accumulation of electronic waste and non-biodegradable material matrices posing significant environmental threats. To address this issue, researchers are focusing on recyclable soft electronics, bio-sensors, and e-inks despite their limitations such as limited shelf-life, restricted temperature, or pH range for optimal activity.[110] Plastics serve as an ideal material matrix for fabricating intelligent systems for the

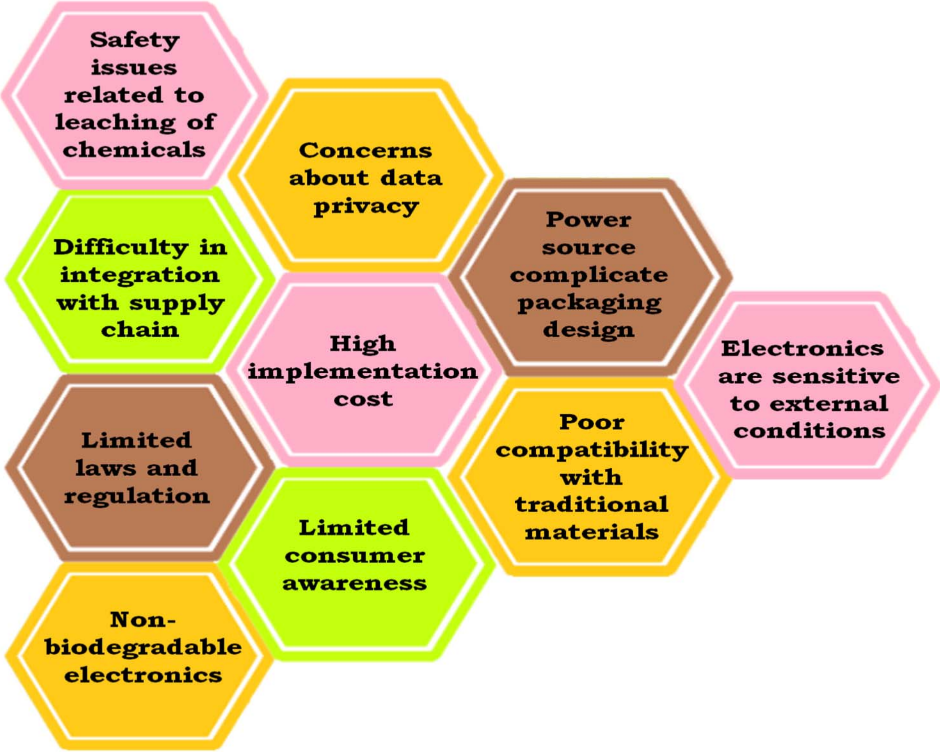

Fig. 7 Challenges encountered in the commercialization of intelligent food packaging.

food and beverage sector owing to their versatility and functionality. Nevertheless, their non-biodegradable nature and potential toxicity raise significant environmental concerns. Despite elevated awareness, the demand and utilization of single-use plastics in food packaging continue to escalate.[111,112] There are several research studies that concentrate on developing environmentally friendly packaging matrices such as bio-composites derived from various agricultural residual byproducts, including rice straw, bagasse, coir pith, sawdust, and corn straw, and molded pulp packaging fabricated using soda-pulped sunn hemp. These eco-friendly packaging matrices exhibit physical properties and mechanical strength comparable to conventional packaging, highlighting their potential as a base for fabricating intelligent packaging systems.[113,114] The cost of intelligent packaging is definitely higher compared to traditional food packaging systems. Moreover, infusing eco-friendly bio-electronic devices further elevates the cost. The initial consumer acceptance may be low owing to the high cost; however this can be improved by communicating efficiently with the consumers *via* campaigns and awareness programs.[115] Researchers conducted an investigation in China to identify the consumer perspectives on the traditional packaging system and emerging packaging technology and identified that most of the participants were neutral towards the current packaging while small percent of participants reported comfort with the traditional food packaging. Interestingly, consumers exhibited a stronger preference for intelligent

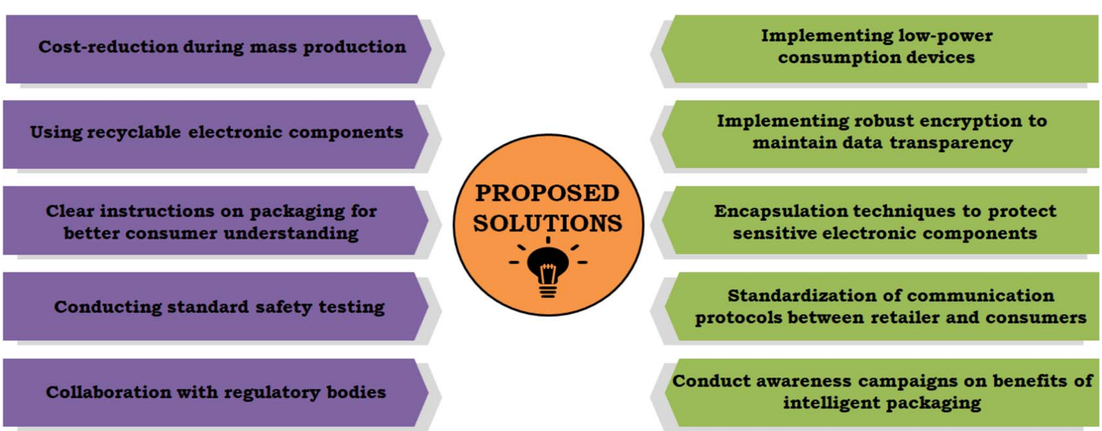

Fig. 8 Potential solutions to overcome the practical difficulties.

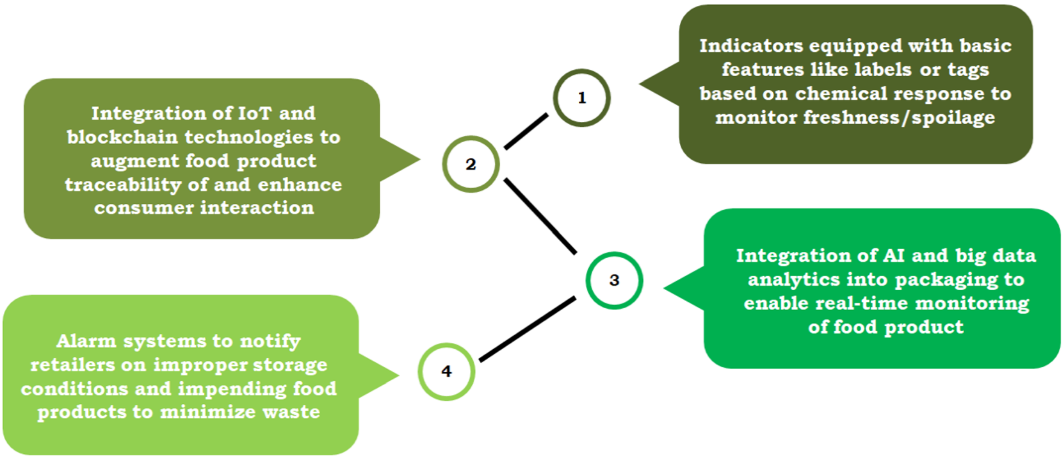

Fig. 9 Evolution of intelligent food packaging.

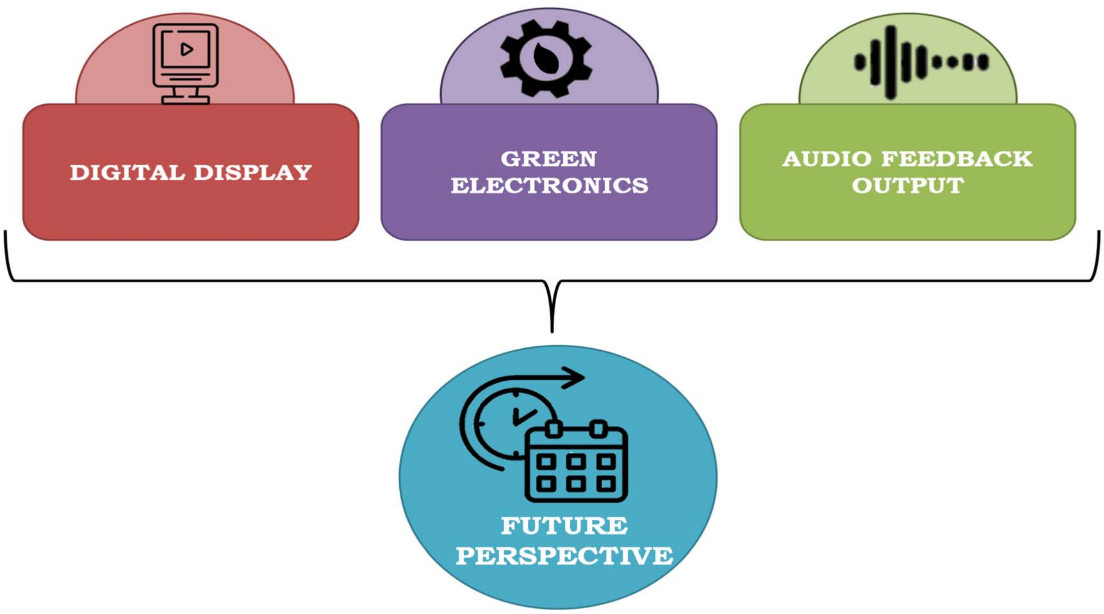

Fig. 10 The future of intelligent packaging systems.

packaging compared to active packaging.[116] The sensors in intelligent packaging are placed on the external surface and are not in direct contact with food. Nevertheless, there is a risk of chemicals and volatile molecules from sensors leaching into the food over time, classifying them as indirect food additives. Furthermore, the regulations and standards for food packaging vary from one country to another making it essential for intelligent packaging to adhere to several food safety requirements across multiple regions.[6] Fig. 7 and 8 illustrate the summary of several other limitations, challenges, and potential solutions.

5. Future directions

The future of intelligent food packaging is moving towards "green electronics" driven by the intense demand for eco-friendly advancements in technology. Green electronic devices are fabricated using non-toxic, organic, and conductive materials that are biodegradable and environmentally safe. These devices integrate sensors and indicators with low-power consumption, addressing multiple global environmental concerns. However, the color-changing responses are not easily distinguishable by all users. To augment the clarity and reduce ambiguity in the visual response, a digital display of output is proposed to offer precise information. Furthermore, to facilitate the accessibility of intelligent packaging to visually impaired people, voice-output-enabled packaging could be introduced, providing multilingual support for exported products and hands-free interaction for automated alerts. Fig. 9 depicts the evolution of intelligent packaging and Fig. 10 illustrates the future directions of intelligent packaging systems.

6. Conclusion

The key findings of the review highlight intelligent packaging as a promising and sustainable innovation in food packaging. The objectives of the review have been successfully achieved by bridging the gap between the underlying mechanisms and practical applications of intelligent packaging. This technology enables interactive communication, real-time monitoring, and analytics along the supply chain thereby predicting spoilage and reducing food waste. The convergence of smart technology and food packaging has the potential to redefine how we perceive, interact with, and consume food, leading to an innovation that benefits both industrialists and consumers. The ability to track the entire lifecycle of food products, from production to consumption, not only enhances food safety by enabling swift responses to potential issues but also bolsters transparency and accountability in the industry. In contrast, navigating the challenges of commercialization by manufacturers necessitates extensive study, resulting in substantial implementation in the near future. In conclusion, the application of intelligent packaging is a viable strategy for offering a guarantee of the quality and safety of food products.

Data availability

The data that support the article are available from the corresponding author upon reasonable request.

Conflicts of interest

The authors declare no conflicts of interest.

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