Discover Sustainability

Review

A comprehensive review to evaluate the synergy of intelligent food packaging with modern food technology and artificial intelligence field

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Abstract
This study reviews recent advancements in food science and technology, analyzing their impact on the development of intelligent food packaging within the complex food supply chain. Modern food technology has brought about intelligent food packaging, which includes sensors, indicators, data carriers, and artificial intelligence. This innovative packaging helps monitor food quality and safety. These innovations collectively aim to establish an unbroken chain of food safety, freshness, and traceability, from production to consumption. This research explores the components and technologies of intelligent food packaging, focusing on key indicators like time–temperature indicators, gas indicators, freshness indicators, and pathogen indicators to ensure optimal product quality. It further incorporates various types of sensors, including gas sensors, chemical sensors, biosensors, printed electronics, and electronic noses. It integrates data carriers such as barcodes and radio-frequency identification to enhance the complexity and functionality of this system. The review emphasizes the growing influence of artificial intelligence. It looks at new advances in artificial intelligence that are driving the development of intelligent packaging, making it better at preserving food freshness and quality. This review explores how modern food technologies, especially artificial intelligence integration, are revolutionizing intelligent packaging for food safety, quality, reduced waste, and enhanced traceability.

Keywords Intelligent packaging · Data careers · Indicators · Sensors · Artificial intelligence

1 Introduction

Food packaging plays a critical role after processing, safeguarding the product from contamination and damage. Its significance lies in safeguarding food quality and ensuring food safety during the entire shelf life of the product. This ensures that consumers receive a valuable product that meets their preferences [1–3]. The key roles of packaging encompass protection, preservation, containment, convenience, communication, reduction of food waste, traceability, marketing, information, and tamper indication [4, 5]. When developing and designing packaging, it is critical to examine the

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features of the product, the properties of the package material, and how the product and packaging interact [4, 6]. The transition from conventional packaging to innovative packaging has evolved in conjunction with the advancement of product quality, heightened human expectations, technological progress, the globalized market, regulatory demands, increased consumer awareness, and heightened concerns regarding food safety [2, 7, 8]. This resulted in a new arena for packaging, active packaging (AP) and IP [7, 8]. Traditional packaging primarily served a passive role as an inert barrier [9]. AP works actively to extend shelf life and ensure product quality and safety by facilitating interactions between the product, package, and environment [10].

While AP technology encompasses various packaging functionalities, its primary focus is on increase product shelf-life [11]. The emergence of IP and Smart Packaging (SP) has introduced advanced packaging technologies [12]. A clear distinction between SP, IP, and AP has not been fully described, potentially limiting their respective utility [7, 13]. IP emphasizes enhanced communication, whereas AP prioritizes improved protection [14]. Traditional packaging, IP, and AP often work synergistically to achieve comprehensive packaging solutions [15]. IP facilitates information flow through data layers, processing, and an information highway, enabling monitoring of internal and external packaging environments. It effectively communicates food product conditions, facilitating timely decision-making and actions based on real-time data access. Business data and models are integrated to enable functionalities such as managing inventory, checking out products, and tracing products [7]. In the context of IP, comprehensive information is offered not only about the product itself but also about its history [16]. Compared to existing traceability systems with limited variabilities, IP proves to be more effective [2]. Packaged products undergo changes such as biological, physical, chemical that can result in spoilage, making it difficult for consumers to detect and assess. Consequently, consumers often question the suitability of a product for consumption when there are minor deviations from the norm [5]. Typically, tests are conducted at the industrial level during production and before dispatch, while post-dispatch testing until consumption is infrequent for packaged products. IP has the potential to address this gap. Notably, IP does not directly interact with the product itself [17]. Quality features, environmental conditions, the components of quality indicators, and their function as data carriers collectively constitute a basis for categorizing IP systems [5]. In IP systems, there are three major technologies in use namely indicators, data carriers, and sensors [2, 18]. In addition to the integration of physico-chemical equipment, there's a noticeable trend towards incorporating artificial intelligence (AI) into intelligent packaging systems. This study is designed to provide an exhaustive examination of the diverse applications, technologies, advantages, and limitations of intelligent packaging (IP) within the area of food technology. Its primary objective is to enhance food safety and quality across the entirety of the supply chain, spanning from the initial stages of production to the ultimate point of consumption. The current comprehensive review seeks to explain the potential avenues for future advancements in the integration of AI with intelligent packaging in the field of food technology. This combination of AI and IP holds great potential in further improving food quality and freshness monitoring, ensuring that consumers receive safer and higher-quality food products.

2 Comprehensive literature assessment

2.1 Intelligent food packaging

As per the legal definition explained by the European Union, IP encompasses an element facilitating the surveillance on the condition of packaged food items or the ambient conditions covering the food throughout its transportation and storage phases [19]. IP has the capability to communicate by acquiring, storing, processing, and sharing information across the entire supply chain [7]. Integrating the concept into packaging materials might raise concerns about food products prices [16]. Nonetheless, IP yields notable benefits, including improved safety, enhanced product quality, reduced waste, and facilitation of inventory management [7]. IP systems offer timely responses [20, 21], while indicators, sensors, and data carriers are utilized to achieve intelligent functionality [16]. IP demonstrates rapid growth, progressing at a double-digit rate. Simultaneously, items such as time–temperature indicators and intelligent labels/tags are becoming increasingly prevalent in the market [22]. IP functions as a quality gauge, delivering augmented convenience and elevated security against theft. The primary technologies of IP include Indicators, Data Carriers, and Sensors, which can be described as follows.

Indicators aim to enhance convenience and offer accurate quality information [2]. Sensors are specific devices used to detect, locate, or measure chemical or physical properties such as energy or matter [2]. Data carriers enable efficient information flow within the supply chain [2]. These IP's ensure automation, traceability, counterfeit protection, and theft prevention by storing and transmitting essential information. Data carriers store and facilitate the transfer of data, whereas indicators and sensors are responsible for monitoring and displaying external information [5]. IP has the potential to enhance the efficacy of 'Hazard Analysis and Critical Control Points' and 'Quality Analysis and Critical Control Points' systems [19, 23], which are devised to accomplish the several objectives. Such as quickly recognize hazardous food items, identify potential health risks and formulating strategies and protocols to prevent, mitigate, or eliminate these issues. Additionally, they aim to identify key processes that significantly impact quality attributes and facilitate efficient improvement of the final food product's quality.

2.2 Indicators

Indicators are able to identify the existence or lack of particular constituents, measuring their concentrations, or assessing the extent of reactivity between different constituents [12]. These indicators exhibit characteristic and observable changes, which can be visualized directly [2, 5, 24]. Indicators are positioned either internally or externally the package, depending on their specific type [2], and lack any receptor or transducer, unlike sensors [21]. Indicators represent a widely utilized IP device [15] and can be categorized into three types: external, attached outside the package; internal, placed within the package; and based on their efficiency in information flow and effective communication with consumer [25, 26].

2.2.1 Time temperature indicators

The shelf life and safety of a product are notably influenced by temperature, as the combination of time and temperature directly impacts the physical kinetics and chemical deterioration [2, 7, 17]. Deviations in temperature can lead to product spoilage, affecting its shelf life by promoting undesirable growth and survival of specific microorganisms [1, 27]. Temperature variations can also lead to alterations in the constituents present within the product. Two distinct kinds of temperature indicators exist: simple temperature indicators and time temperature indicators (TTIs) [28]. Temperature indicators are employed to fulfil the function of indicating if products have been subjected to heating above or cooling below a specified reference temperature. Their primary role is to signal to consumers the potential survival of pathogenic microorganisms and the occurrence of protein denaturation due to procedures like freezing or defrosting [29]. TTIs are utilized to ensure the maintenance of the required temperature within specified time periods at various control points throughout the entire food supply chain [5, 17]. TTIs serve to record the thermal history of the product [1, 6, 30], facilitating the detection of temperature abuse or any instances where the product is kept beyond the specified threshold duration [17]. TTIs are external IPs giving storage information [25]. There are three types of TTIs based on their function: critical temperature indicators, critical temperature/time integrators/partial history indicators and time temperature integrators or indicators/full history indicators [7, 31].

Critical temperature indicators determine whether the product has been exposed to temperatures exceeding or falling below the permissible threshold [31], thereby detecting any fluctuations from the prescribed temperature range. Critical temperature/time integrators/partial history indicators identify whether a product has undergone temperature abuse, leading to changes in product quality [5, 8, 32]. Time Temperature Integrators or Indicators/full history indicator record the complete temperature profile throughout the food supply chain, enabling the detection of any instances of temperature abuse [2, 5, 33].

TTIs can be categorized based on their working principle as chemical, physical, enzymatic and biological systems [1, 15, 24]. Chemical TTI indicates a specific colour by reacting chemically [1]. They are polymerization-based TTI, photochromic-based TTI, and oxidation reaction-based TTI [34]. TTI based on polymerization operates on the basis of a solid-state polymerization process involving a monomer and an acetylene group. In the case of the photochromic-based TTI, it employs a photochromic chemical that is activated by a particular wavelength of light, resulting in a distinctive colouration change as a result of thermally induced fading in a reverse reaction process [1]. The oxidation reaction-based TTI, on the other hand, changes its colour by a redox reaction or a light-induced redox reaction in which the chemical reacts with oxygen in the air [1, 17]. Physical TTI can be categorized based on their working principles, utilizing different physical property discolouration mechanisms, including diffusion-based TTI, nanoparticle-based TTI, electronic TTI, etc. [34, 35]. The enzymatic TTI operates on the basis of a hydrolysis reaction involving an enzyme and its substrate, resulting in a colour change [36]. This colour change can be calibrated by considering various parameters, such as the enzyme type and concentration, the presence of activators or inhibitors, the pH level, and the presence of a buffer [1, 37]. As

Biological TTI, Yeast and lactic acid bacteria based TTIs are commonly employed, while *Streptococcus* based TTIs are also available for use. TTIs based on photonic lattice changes and TTIs relying on thermo-chromic polymer/dye blends are other available options [1].

TTIs play a crucial role in signalling potential microbial survival or denaturation of proteins caused by temperature fluctuations [2, 8]. Their usefulness is based on irreversible time and temperature-dependent changes in the product, which may include chemical, mechanical, electrochemical, enzymatic, or microbiological activities [5, 7, 38, 39]. These TTIs provide measurable values through visible responses, such as colour development, colour movement, or mechanical deformation [40]. They are user-friendly and readily applicable, given their direct impact on food quality and temperature [1]. In the market, the majority of commercially available TTIs are in the form of label-type indicators or tags [17, 41], typically attached to the packaging to monitor time–temperature variations from production to consumption [1, 7]. The commercial adoption of TTIs has witnessed a notable increase in recent years [21]. TTIs represent the most prevalent IP system in use today [22], particularly for foods stored under chilled or frozen conditions [25, 42]. The lactic acid-based TTI employs lactic acid vapor diffusion to detect the time–temperature history of fruits and vegetables, thereby indicating their quality [43]. The Vitsab TTI, developed by Vitsab AB in Malmö, Sweden, utilizes lipase as an enzymatic TTI CheckPoint® to ensure quality assurance at ambient temperatures [39, 41]. The colour of the TTI changes from green to orange/red due to a pH shift caused by the release of fatty acids from lipase activity, indicating it is no longer suitable for consumption (Fig. 1) [39, 44]. The application of alpha-amylase and β-glucosidase estimates the temperature–time history throughout the sterilisation procedure. A laccase-based TTI prototype demonstrates potential in predicting food quality losses attributed to enzymatic modifications, hydrolysis, and lipid oxidation [41, 45]. Commercially available TTIs encompass a range of types, including diffusion-based, chemical-based, photochemical reaction-based, microbiological, polymer-based, enzymatic-based, and barcode-based label TTIs [16, 24, 46]. Table 1 displays several examples of commercially available TTIs.

TTIs play a crucial role in ensuring food quality and safety, which directly influences consumer satisfaction and perceptions [1]. These indicators are designed with a consumer-friendly approach [22], characterized by simplicity, relatively lower cost, and high efficiency [26, 42]. Nevertheless, it is essential to consider potential risks associated with certain TTIs. Even though TTIs are generally tightly attached, organic or inorganic compounds present in some TTIs may migrate into the food, posing potential toxicity concerns. For instance, Acetylene polymerization-based TTI may contain diacetylene compounds with cytotoxic activity, Redox reaction-based TTI may include anthraquinones, a potentially toxic substance, and Nano-based TTI may incorporate toxic inorganic Ag and Au nanoparticles [1]. Thus, careful evaluation of TTIs' composition and safety aspects is essential to mitigate any potential health risks. TTIs primarily monitor the outer surface temperature of the food package rather than directly measuring the actual temperature of the food itself. As a result, the colour change in TTIs may not always accurately reflect the complete temperature profile of the product, posing limitations in accurately forecasting product shelf-life [1]. The implementation of TTIs get considerable costs, which can make manufacturers reluctant to adopt this technology in their packaging [1]. The lack of sufficient knowledge and awareness about food safety management related to TTIs serves as a barrier to their widespread adoption [31]. Successful TTIs should possess certain characteristics, including being low cost, easily comparable, simple, reliable, capable of tolerating ambient temperatures, and having a flexible temperature range. TTIs should present no safety hazards or

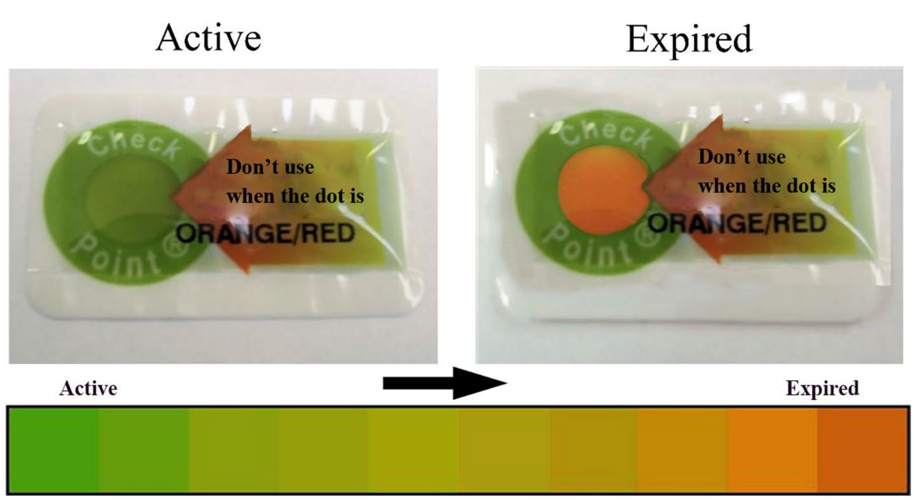

Fig. 1 Colour change in active and expired CheckPoint® TTI [44]

Table 1 Commercially available TTIs and their functions and working conditions

Commercially available TTIs	Function	Category	Storage	Activation	Examples
Commercial diffusion-based TTI	Applied for monitoring the microbial quality of perishable food [41, 47]	Physical	Low temperature	Mixture	3 M Monitor Mark® (3 M Company, USA) [25, 48], TT Sensor™ (Avery Dennison Corporation, USA) [25, 49]
Commercial enzymatic TTI	It operates within diverse food systems by detecting pH changes through substrate and enzyme adjustments and changes in colour [50]	Enzymatic	Low temperature	Mixture	CheckPoint® (Vitsab AB, Sweden) [25, 49], Vitsab indicator (Vitsab Sweden AB, Sweden) [51], TimeStrip® (TimeStrip UK Ltd., Cambridge, UK) [52]
Commercial polymerization-based TTI	Indicate the food product's shelf life by changing the colour of the polymer [1]	Chemical	Low temperature	Room temperature	Lifelines Freshness Monitor® (lifelines Technology Inc., USA) [17], Fresh-Check (TEMPTIME Corporation, NJ, USA) [17, 24, 49], HEATmarker® (TEMPTIME Corporation, NJ, USA) [1]
Photochemical-based TTI	Shows heat exposure using colour-changing ink [53]	Chemical	Room temperature	Light	OnVu™ (Ciba Specialty Chemicals Inc., Switzerland) [49, 54]
Barcode-based label TTI	Barcodes printed with temperature-sensitive ink for cold chain monitoring [55]	Physical	Low temperature	Temperature change	FreshCode™ (Varcode Ltd.) and Tempix® (Tempix AB) labels [55]
Microbiological TTI	Microorganisms at specific temperatures produce acid, causing a colour change via pH indicators [1, 49]	Biological	Low temperature	Mixture	TopCryo™ [55], TRACEO® and eO® (CRYOLOG) [49, 56]
Nanoparticle-based TTI	Nanoparticles change surface when heated, shifting wave numbers into the visible range in food packaging [1]	Physical	Low temperature	Mixture	N/A

N/A denotes not applicable

toxicity concerns, effectively convey the necessary information, and have a considerable pre- and post-activation shelf life [24]. TTIs must enhance functionality, improve barrier properties, and reduce costs. Evaluating toxicology is essential to prevent hazardous compound migration, ensuring consumer safety. Improving time and temperature accuracy and accounting for other shelf-life factors are necessary. As part of IP, TTIs help meet quality and safety expectations beyond traditional packaging.

Recent consumer study in France, Greece, Germany, and Finland revealed both favourable and negative opinions of TTIs for packaged meat or poultry and fish [57]. TTIs are perceived as improving cold-chain management prior to and following purchase, functioning as an additional factor for food selection, and generating excitement due to their originality [58]. Some people have negative views on TTIs. Concerns include increased food waste due to misinterpretations, and potential manipulation by retailers who might remove the indicators. Additionally, skepticism exists regarding the technology's reliability, confusion about the TTI messages, and potential conflicts with other freshness indicators [57, 58].

2.2.2 Gas indicators

Gas indicators directly contact, and monitor gases produced during food deterioration, ensuring food quality and safety [59, 60]. The air inside food packaging isn't constant. It's influenced by the food itself by breathing and moisture release of fresh produce, microbial spoilage and the packaging material permeability along with surrounding conditions like temperature and leaks. These modifications have a direct impact on the quality, safety, integrity, and shelf-life of packaged food items [38]. Gas indicators determine food quality based on inside atmosphere. The sensor monitors packaging environment and triggers responses, displaying the real indicator's status. Placed within the package, they respond to gas changes [38, 59, 61]. Some may lose colour due to moisture. Indicators show irreversible colour shifts in response to gas composition. They monitor oxygen, carbon dioxide (CO_2), ethanol, hydrogen sulfide, and water vapor levels, which often strongly correlate with spoilage development [38, 59]. Many devices utilize redox dyes, reducing agents, and alkaline components. Encapsulation or coating techniques enable UV-activated colourimetric indicators to signal reduced dye leaching [2, 59, 62]. A visual CO_2 indicator device is created, incorporating polymeric films with chemical dyes like bromocresol purple or methyl red, and polypropylene resin with calcium hydroxide as a CO_2 absorbent. This estimates the fermentation degree in kimchi, a traditional fermented vegetable-based food in Korea, without damaging the packaging during storage and distribution (Fig. 2) [38, 63–65]. These indicators offer information on the CO_2 levels in packages during transportation and storage, along with early detection of food spoilage. Regardless of the temperature, the system works on the basis of pH-dependent colour change [65].

Variations in CO_2 and oxygen content can lead to microbial decomposition and quality degradation. Hence, in some applications, a CO_2 indicator can also act as a leakage indicator. Colourimetric CO_2 indicators that use natural extracts such as lysine, polylysine, and anthocyanin, like oxygen indicators, have been created to detect pH changes. In experiments involving poultry meat, researchers examined both aqueous-type and label-type indicators with various CO_2 concentrations, detecting apparent colour shifts from azure to deep purple [60, 66].

2.2.3 Freshness indicators

Microbial contamination in foods leads to reduced shelf life and increased foodborne disease risks. Consequently, the food industry, merchants, and food safety regulatory authorities are keenly interested in developing accurate, cost-effective, quick, trustworthy, and nondestructive ways to check real-time food product freshness. Freshness indicators play a crucial role in monitoring the quality of food products during storage and transportation [5, 67]. The loss of freshness in food products can occur due to unfavorable conditions or surpassing the designated shelf life. Freshness indicators assess the product's microbiological quality by reacting to metabolites produced during microbe growth and the associated spoiling or reduction in freshness. They can also indicate instances of temperature misapplication or package leaks [5, 68]. A freshness indicator is a packaging technique specifically developed to provide direct information about the quality of the product, not just alerting consumers about temperature abuse or package leaks. Freshness indications must be put within the package for contact with the chemicals. The detection of this information can be achieved using various methods, depending on the type of indicator [69] (Table 2). To monitor the quality of packaged food, freshness indicators use microbial growth metabolites to identify changes occurring inside the food product, such as CO_2, total volatile basic nitrogen (such as ammonia, dimethylamine, and trimethylamine), and H_2S [70, 71].

Fig. 2 Indicators to detect fermentation degree of kimchi

These indicators function by utilizing interactions with growth metabolites like CO2, oxygen, ethanol, lactic acid, glucose, and other volatile organic molecules. The aim is to detect chemical changes or microbial growth within the packaging. These indicators require direct contact with the food. Metabolites such as carbon dioxide, volatile nitrogen compounds, ethanol, biogenic amines, ATP degradation products, glucose, sulfuric compounds and organic acids are indicative of product quality. A sensor label developed by FQSI (Food Quality Sensor International Inc., Lexington, MA, USA) that can recognize biogenic amines is an example of a freshness indication [72, 75]. SensorQ™ is customarily tailored for beef and poultry applications, with a primary emphasis on enhancing the detection of microbial growth and monitoring gases within the container, notably focusing on sulfide gas [76]. This sensor sticker changes colour from orange to brown upon detecting a significant level of bacterial growth (Fig. 3) [24].

Biogenic amine sensors are based on the working theory of amine oxidases or transglutaminase [72, 77]. Lactic acid sensors function based on NAD^+ dependent lactate dehydrogenase, hydrogen peroxidase, lactate oxidase and flavocytochrome b_2 activities [78]. Glucose sensors utilize immobilized glucose oxidases on the electrode surface, catalyzing the oxidation of glucose [79]. The intelligent sensor label, named RipeSenses (Jenkins Group, Auckland, New Zealand), serves as a calorimetric indicator for determining the optimal maturity level of fruits, particularly pears. The functionality is based on the identification of natural aromatic molecules released by ripening fruit. The sensor's initial red colour represents crispness, transitioning to orange to denote firmness, and ultimately turning yellow to indicate full ripeness and peak juiciness of fruits, particularly in pears. When the sensor achieves the intended ripeness colour, refrigerating the fruit substantially decelerates the ripening process [63, 72]. This technology has found application in various other fruits, including kiwifruit, melon, avocado, mango, and stone fruit [63].

Before achieving widespread commercial use, several limitations related to freshness indicators relying on broad spectrum colour shifts require attention. The lack of specificity can lead to colour changes indicating contamination even in items without noticeable sensory or quality deterioration. The existence of specific target metabolites doesn't always equate to poor quality. A more accurate correlation is needed between product type, target metabolites, and

Table 2 Fundamental concepts of indicators utilizing metabolites

Metabolites	Food products	Indication	Sensors	References
Glucose/Lactic acid	Meat, Fermented food	Colourimeter used to determine pH	Redox reaction-based electrochemical sensor	[69]
Carbon dioxide	Meat, Fermented food	pH sensitive dye reaction	Electrochemical sensor based on redox reaction	[69]
Oxygen	Vegetable, Meat	Fluorescence optical sensors, colourimeters with pH-indicator dyes	Electrochemical sensor by Zirconia, laser	[72, 73]
Biogenic amines (tyramine, cadaverine, putrescine, histamine)	Fish, Meat (Poultry, Beef, Pork)	Dyes that change colour in response to pH	Electrochemical biosensor by enzyme redox reaction or spectrophotometric assay based on enzymatic determination	[69, 72]
Ethanol	Seafood, Fresh produce	Dyes that change colour in response to pH	Enzyme-based test strips	[72]
ATP degradation products	Meat, Seafood	Redox reaction-based colour change	Enzymatic determination test strips and electrochemical biosensors	[72, 73]
Sulfuric compounds	Poultry meat, Seafood	The interaction with hydrogen sulphide changes the colour of the thin silver coating to an opaque pale brown	Radio frequency readable, package integrated sensors, Nano-scale layer of silver	[72]
Volatile nitrogen compounds (ammonia, dimethylamine, trimethylamine)	Seafood	pH sensitive dyes as a visible change in colour	Headspace-gas chromatography, Semiconductor gas sensors, Ammonia ion-selective electrodes	[72, 74]

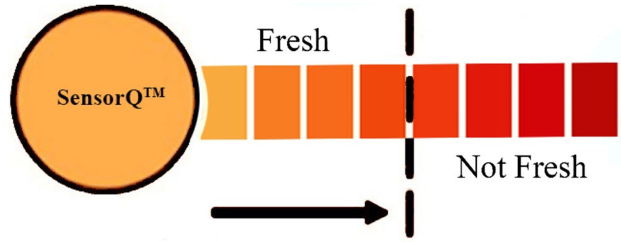

Fig. 3 Working principle of c [24]

organoleptic quality and safety. Unless a reliable indication of genuine spoilage is guaranteed, producers might hesitate to adopt indicators due to the potential for false-negative results [80].

2.2.4 Pathogen indicators

In addition to the aforementioned systems designed to respond to food product spoilage. There have been developments in indicators aimed at directly detecting contamination of meat and meat products by pathogenic microorganisms. These indicators, compact analytical devices, are capable of detecting, recording, and transmitting information about biochemical reactions caused by pathogens [7]. These devices include bioreceptors for analyte detection and transducers for signal conversion. Bioreceptors are organic or biological materials like enzymes, antigens, microbes, hormones, or nucleic acids, while transducers can be electrochemical, optical, or calorimetric. These sensors in food packages also change colour to indicate potential issues [17, 38, 52, 81]. In the food chain, it is essential to monitor and identify specific pathogenic microorganisms that can lead to various diseases and pose a risk to human health. These indicators offer insights into the microbiological situation, particularly on perishable foods like meat, fish, and poultry. They furnish information about food product quality by detecting biochemical alterations and the proliferation of contaminating microorganisms [82].

Lawrence Berkeley National Laboratory created a specialized indicator material to detect *Escherichia coli* 0157 enterotoxin. This material, integrated into packaging, contains cross-polymerized polydiacetylene molecules, appearing deep blue. Specific toxin-binding molecules are confined in this matrix. Upon toxin interaction, the film shifts colour from blue to red [8]. When the microorganism is present, the barcode becomes uninterpretable. Lawrence Berkeley National Laboratory has devised distinct indicator materials to detect *Escherichia coli* 0157 enterotoxin. These pathogen indicators induce colour changes in food packaging to signal consumers and retailers against consuming the food. An exemplar of a commercially available pathogen indicator is the Food Sentinel System™ (SIRA Technologies, California, USA), revealing pathogen presence in meat packaging. Salmonella sp., *Escherichia coli* 0157:H7, Campylobacter sp. and Listeria sp. adhere to the membrane, integrated with the barcode. The emergence of a contaminating pathogen initiates the development of a distinct dark band in the barcode, resulting in the barcode becoming unreadable during scanning [26, 29, 52, 83]. Toxin Guard™, created by Toxin Alert in Ontario, Canada, represents another pathogen indicator. It encompasses biochemical sensors that incorporate antibodies within a polyethylene-based plastic packaging. This system is adept at detecting pathogens including Salmonella sp., Campylobacter sp., *Escherichia coli*, and Listeria sp. [49]. Volatile amines can be determined based on polyaniline films, cellulose, and bacterial cellulose membranes, which are supplemented with methyl red or curcumin [84]. Zinc oxide nanoparticles were developed in meat packaging to delay the growth of microflora and retard lipid and protein oxidation [85]. Gelatin-sodium alginate films containing beetroot peel extract work as antioxidants and are used in food packaging for meat preservation [86]. Freestanding films of antimicrobial conductive nanocomposites, comprising poly sulfobetaine methacrylate and bacterial nanocellulose, were developed. These films exhibit characteristics desirable for intelligent food packaging, including ultraviolet barrier properties, moisture absorption capabilities, and antimicrobial activity effective against foodborne pathogens [87].

2.3 Sensors

A sensor can be defined as a device employed for the detection, localization, or quantification of energy or matter. This device generates a signal in response to the detection or measurement of a specific chemical or physical property [5, 88]. Utilizing a sensor presents an alternative to the typical analytical techniques, which can often be expensive, time-consuming, and result in destructive processes [19]. In intelligent food packaging, different types of sensors are used. Typically, monitoring of packaged food focuses on factors such as temperature, gas production, humidity levels, and the growth of microorganisms [62, 89]. Sensors typically comprise two fundamental elements: a receptor for detecting and identifying diverse physical or chemical parameters and a transducer to convert these readings into a measurable form of energy [5, 54, 88]. Sensors employed in intelligent food packaging can be primarily classified into categories such as gas sensors, chemical sensors, biosensors, printed electronics, and electronic noses [17, 19]. There exist certain challenges for the practical implementation of sensors for commercial purposes. Ideally, these indicators should be compact, flexible, cost-effective, durable, and highly sensitive. Additionally, they must comply with strict regulations and be compatible with food safety standards [19].

2.3.1 Gas sensors

Gas sensors can detect and quantify gases, such as ethylene, carbon dioxide, sulfur dioxide, ethanol, ammonia and hydrogen sulfide, released during product spoilage [5, 90, 91]. Metal oxide semiconductor field-effect transistors, amperometric oxygen sensors, piezoelectric crystal sensors, potentiometric carbon dioxide sensors, and organic conducting polymers are some of the established systems for gas detection [2]. Recent advancements have led to the development of sensors addressing certain limitations, including fouling of sensor membranes, cross-sensitivity to hydrogen sulfide and carbon dioxide, and the depletion of analytes like oxygen and CO_2 [2, 24].

CO_2 sensors are typically classified into two categories: optical and electrochemical, based on the type of transducer [89, 92]. CO_2 sensors can be categorized as Non-Dispersive Infrared (NDIR) Sensors, Photoacoustic Sensors, Wet Conductometric Sensors, Severinghaus-type Sensors, Ion-Selective Field-Effect Transistor Type Sensors, Dye-Based Sensors, Optical Fiber Sensors, Adsorption by Metal Oxide-Based Sensors, Graphene-Based Sensors, Potentiometric Sensors, and Ionic Liquids-Based Sensors in various types [92]. Conventional and commercial approaches for detecting gaseous and dissolved CO_2 involve NDIR sensors and Severinghaus-type sensors, respectively. NDIR instruments, despite their high precision, are expensive, bulky, and susceptible to contamination by water vapor and other substances. Additionally, they require destroying the packaging for gas analysis, hindering their everyday use. Therefore, there's a need for compact and affordable alternatives [89]. Optical carbon dioxide gas sensors have immense potential for use as food packaging indicators. Dry optical sensors with pH-sensitive dye indicators are especially interesting for monitoring CO_2 levels and functioning as spoiling indicators in food packaging [24, 54, 93]. In food packaging, water-based CO_2 indicator inks are common, but challenges like humidity interference, lifespan, safety, cost, and proton generation must be addressed to realize the full potential of pH-based sensors [94]. While they exhibit relatively lower sensitivity to CO_2 compared to solvent-based sensors, they provide extended shelf life and faster response times. Nonetheless, more research is essential for the development of sensors tailored for food applications. Photonic crystal sensors hold promise due to their cost-effectiveness, long lifespan, and suitability for a range of analytes [89, 94].

2.3.2 Chemical sensors

The chemical sensor, known as the receptor, consists of a chemically selective coating. It can identify specific chemicals or gases based on their presence, activity, composition, and concentration through surface adsorption. The transducer then converts the observed presence of these specific chemicals into signals. Transducers can be classified as either active or passive, depending on their requirement for external power during measurement [19]. Carbon nanomaterials, including nanoparticles, graphene, graphite, nanofibers, and nanotubes, find application in chemical sensors due to the outstanding electrical and mechanical attributes, in addition to their substantial specific surface area [19, 95]. Nanotechnology-based chemical sensors offer diverse applications in the food industry. They can identify pathogens, chemical contaminants, spoilage, and product tampering, ensuring food safety, quality control, and packaging security [17, 96]. Wearable chemical sensors have gained attention in academia, primarily for identifying hazardous chemical threats like pesticides, narcotics, and explosives [97]. Given the critical issue of pesticide misuse within the food industry, an immediate demand exists for sensors to oversee food safety. As a response, fingertip electrochemical sensors have been introduced to the field of pesticide sensing. These wearable chemical sensors are integrated into robotic gloves for assessing attributes such as sweetness influenced by glucose, sourness affected by ascorbic acid, and spiciness influenced by capsaicin on different fingers [98, 99].

2.3.3 Biosensors

A biosensor is an analytical device utilized for quantifying specific target molecules within a sample. Generally, a biosensor encompasses a bio-recognition element, which can be an aptamer, antibody, or enzyme, known for its specific binding to the target molecule [100, 101]. In biosensors, biological components are coupled with physicochemical detectors, offering significant advantages for detecting and analyzing food contaminants. This synergy results in heightened sensitivity and specificity due to precise target recognition [102]. Inside a biosensor, the transducer converts a physicochemical or biological signal into a measurable form. These signals manifest in diverse ways, encompassing optical manifestations like colourimetry, fluorescence, chemiluminescence, and surface plasmon resonance. They manifest as electrical signals, including voltammetry, impedance, and capacitance [100, 102, 103]. Biosensors are widely utilized for the recognition, recording, and quantification of diverse substances, encompassing allergens, sugars, amino acids, alcohols, lipids, pathogens, and other analytes [2, 7, 19]. They play a crucial role in identifying target metabolites formed as a result of the complex biochemical reactions that occur during food degradation [104, 105]. There are various types of biosensors based on different operating principles. These include electrochemical biosensors [106], optical biosensors [107], immobilized-based biosensors [108], piezoelectric biosensors [109], microbial biosensors [110], and nanomaterials-based biosensors [111]. Nanomaterial-based biosensors present key advantages, including enhanced selectivity and sensitivity, specific target recognition, shorter analysis times, and improved signal readout. These biosensors exhibit the capacity to detect an extensive array of substances, spanning pathogens, toxins, heavy metals, pesticides, veterinary drugs, and illicit additives [102, 112]. The fundamental differentiation between a biosensor and a chemical sensor is rooted in the composition of the recognition layer. In biosensors, this layer consists of organic or biological materials, whereas in chemical sensors, the receptor takes the form of a chemical compound. Biosensors exhibit greater specificity in monitoring food freshness compared to freshness indicators [15, 113]. Examples of developed biosensors include the Food Sentinel System by SIRA Technologies (USA), Toxin Guard™, and Flex Alert biosensors [2].

2.3.4 Printed electronics

Printed electronics technology is an interdisciplinary field that combines printing and electronics, enabling the creation of electronic circuits on flexible substrates using electrically functional inks [17, 114, 115]. Printed electronics use different printing techniques like inkjet printing, screen printing, nanoimprinting, and soft lithography. These methods manufacture electronic circuits on flexible substrates such as polyimide, polyether ether ketone, polyethylene terephthalate, transparent conductive polyester, steel, or paper [19, 114, 116]. In printed electronics, traditional inks are swapped for functional inks that can conduct, block current, and change colour [15, 117]. Unlike standard inks made up of pigments, solvents, resins, and polymers, functional inks incorporate specialized elements, such as metal particles [15, 118]. These include conductive, chromogenic, photochromic, and thermochromic inks, and they play a vital role in intelligent food packaging systems, particularly in printed electronics [15]. Printed electronic sensors are lightweight, flexible, portable, potentially foldable, thin, and can be tailored to operate uniquely on various substrates [19, 119].

2.3.5 Electronic noses

Electronic noses replicate the mammalian olfactory system to consistently and reproducibly identify and categorize aromatic compositions in odorous substances, generating unique responses for each flavor or odor [17, 120]. The sensors integrated into electronic noses exhibit reactivity towards both odorous and odorless volatile compounds [121, 122]. It is designed to perceive and differentiate complex odor compounds through an array of sensors that are broadly sensitive and non-specific. These sensors are treated with a range of odor-sensitive biological or chemical agents, enabling them to detect a variety of odors [123]. The utilization of pattern recognition techniques is crucial for qualitative odor analysis or the discernment of multiple compounds in a given mixture. Multicomponent analysis methods are employed for the quantitative assessment of one or more compounds within the mixture [121]. In commercialized electronic noses, the main technologies used include metal oxide semiconductors, metal oxide semiconductor field-effect transistors, conducting organic polymers, and piezoelectric crystals [120]. Electronic nose systems have demonstrated success in assessing the quality of various food items, including fresh yellowfin tuna and vacuum-packed beef [8, 124, 125]. These systems are applicable for evaluating the quality of fruits and vegetables by analyzing their emitted odors. For example, [126] employed an electronic nose to investigate the volatile compounds produced during different ripeness stages of tomatoes. Similarly, [127] employed electronic nose technology to evaluate the quality of modified atmosphere-packed broiler chicken cuts. Recent advancements in technology have introduced nano material-based electronic noses, which have the potential to detect molecules at near-single molecule levels, resulting in faster response kinetics. The high integration density offered by these materials can lead to the development of smaller-sized devices with superior performance when compared to existing sensor technologies [128, 129].

2.4 Data carriers

Data carriers, also recognized as automatic identification devices, constitute a foundational category within SP. Typically compact and cost-effective labels or tags, they are affixed to a product's primary, secondary, or tertiary packaging, with the aim of augmenting quality and safety through streamlined communication along the supply chain. These carriers store and transmit data, enabling functions such as automation, traceability, theft prevention, counterfeit protection, and a multitude of other capabilities. Barcodes and Radio Frequency Identification Tags (RFID), categorized as a convenience-enhancing intelligent system, plays a key role as a data carrier within the food industry [2, 5, 130]. These technologies are employed individually or synergistically, contingent upon the context [131, 132]. In tandem with technological progress, additional IP mechanisms, such as biosensors are seamlessly integrated with RFID technology, offering a substantial enhancement in the quality and safety of food products.

2.4.1 Barcodes

Due to their cost-effectiveness and ease of use, barcodes have become widely popular, especially in large-scale retailing, following the introduction of Universal Product Code (UPC) barcodes in the 1970s [7]. Barcodes revolutionized retail by eliminating manual tasks in inventory management, stock documentation, and checkout. Their integration with event stream processing software allows for smart warehouse management [2, 133]. UPC is comprised of a series of parallel bars and spaces meticulously arranged to encode 12-digit data, which is deciphered by an optical barcode reader [2, 7, 130, 134]. The progression of barcodes encompasses three principal phases. The initial phase comprises one-dimensional (1-D) barcodes, constituting the first generation, where storage capacity is confined to the manufacturer's identification and item numbers. The fundamental mechanism of 1-D barcodes mirrors the traversal of a laser beam horizontally across vertical code bars. The duration of beam exposure to the symbol's black bars and light regions is recorded during its passage [2]. Subsequently, a lookup table is utilized to decode distinct characters, spanning different periods [7]. To address the issue of limited storage capacity inherent in 1-D barcodes, a subsequent development known as Reduced Space Symbology (RSS) was introduced [2, 135]. RSS brings forth numerous advancements in product identification and traceability within the grocery industry. Notably, the RSS 14 Stacked Omni directional barcode encodes the complete 14-digit Global Trade Item Number, allowing its application as a narrow symbol on products with restricted space, such as fruits [7, 136]. To significantly augment the storage capacity to accommodate up to 74 alphanumeric characters, the RSS expand barcode was devised. This expansion facilitates the encoding of additional information, including batch numbers and packaging-related data [2, 7]. The third-generation two-dimensional (2-D) barcodes, combining dots and spaces in a matrix, were developed. In this type of barcode, data can be encoded using various modes, including numeric, alphanumeric, binary, kanji, or logographic Chinese characters [2, 137]. An exemplar showcasing the enhanced data density achievable within confined space using 2-D barcodes is the Portable Data File 417, which can accommodate up to 1.1 kilo bytes of data within the dimensions of a UPC barcode. This underscores how 2-D barcodes permit the encoding of significantly greater information [2, 7].

Reading 2-D symbology necessitates a transition to 2-D simultaneous reading scanners. Technological progress has rendered scanners more potent and economically viable, accompanied by innovations like wireless handheld barcode scanners, now commonplace in numerous retail establishments [7]. Ensuring the quality of barcode printing on food packages is of paramount importance, and extensive research has been conducted to determine the optimal printing conditions. The ideal process parameters for maximizing barcode quality involve a feed rate of 200 m/min, an operational temperature of 220 °C, a contact pressure of 45 kPa, and a kinetic velocity of 90 mm^2/sec [138]. Likewise, in today's business environment, spanning across industries including the food sector, barcode technology plays a vital role in tracking both the internal and external product flows. This widespread adoption is attributed to its ability to accelerate data transmission and enhance information accuracy.

2.4.2 Radio frequency identification tags

RFID tags represent a form of wireless communication classified within the area of informative and responsive packaging. They operate based on the fundamental principle of product/object identification through radio frequency utilization. Typically, an RFID system comprises three core components: a transponder, a reader, and associated software [7, 139, 140]. The underlying operational mechanism involves the transmission of signals via radio waves to activate the tag. Once activated, the tag responds by emitting a wave back to the antenna, which is then converted into data. This captured data is then channeled to the software for analysis and decision-making processes [7]. The tag integrates a circuit with an Electronic Product Code, functioning as a unique tracking identifier. The reader receives the broadcast signal and forms a network link between the tag and system software. The entire setup is managed by middleware, which can take the form of a local network or a web server [2]. The working mechanism of the RFID system can be shown as in Fig. 4.

RFID can be categorized based on frequency and internal power source, with frequency classes including low-frequency, high-frequency, ultrahigh-frequency, and microwave frequency [141, 142]. Subsequently, various types of RFID tags have been developed, including Active RFID tags, Passive RFID tags, Semipassive RFID tags, and Ultra High-Frequency RFID tags [142]. Passive tags operate using ultra-high frequency and contain a microchip, with a reading range of up to 15 feet [7, 142, 143]. In contrast, active tags are more costly as they incorporate a battery to power the microchip's circuitry and enable signal transmission to the reader. Consequently, the reading range for active tags can extend up to 100 feet [2, 7, 144]. Active tags support tag-to-tag communication, and another type, the semi-active tag, includes a battery for memory backup and data support [145]. RFID tag read range is affected by variables such as tag type, reader characteristics, frequency, and potential interference. These can be adjusted for specific needs. RFID tags provide real-time information, used commercially in supply chain management, inventory control, traceability, and asset tracking across industries, streamlining operations and enhancing product quality and safety [146, 147]. They are also used beyond the food industry by various entities, including Walmart and Metro Group, which have mandated RFID tag usage on shipping crates and pallets [148]. Some protocol standards, including ISO 18000, play an important part in the regulation of RFID systems. ISO 18000, for instance, specifies the working frequency ranges and other essential parameters for RFID systems, ensuring consistency and compatibility in their operation [149].

Initially, RFID tags in the food industry were limited due to high production costs, but as hardware costs decreased, their use expanded. RFID technology now serves various food industry functions, including traceability, product identification, shelf life prediction, cold chain management, livestock oversight, and feeding regulation [2, 7, 150]. RFID tags are sometimes combined with responsive materials in labels to provide real-time data on food package contents, offering insights into food quality. When attached to polymers, RFID tags can interact with food analytes like biogenic amines, producing a detectable signal due to changes in the tag's electromagnetic potential [151]. RFID tags find applicability in the monitoring of perishable commodities requiring stringent shipping conditions. Models can be calibrated to evaluate the preservation status of apples based on variations in ethylene, ethanol, and acetaldehyde levels [145]. The freshness assessment of fish employs RFID tags integrated with sensors for measuring temperature, humidity, and the presence of volatile amine chemicals [150, 152]. The RFID system has evolved into a tracking tool that aids in the authentication and validation of Halal certificates and logos [153]. In the area of food, chip-less RFID sensors have emerged as advanced technology for identification and sensing. Various types of tags, including time-domain tags, frequency tags, hybrid tags, and image-based tags, are integrated with different sensor types. These sensors offer insights into freshness, temperature, microbial quality, and packaging integrity, enabling functions like inventory control, product tracking, quality monitoring, and early warning provision [146, 154].

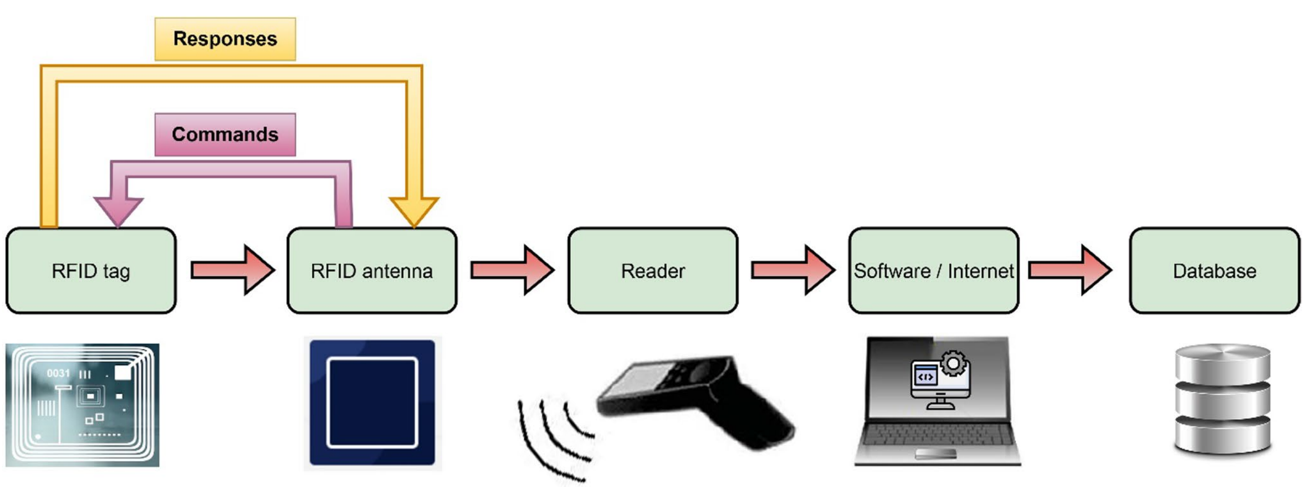

Fig. 4 Working mechanism of RFID system (designed by authors)

In today's world, RFID technology serves as a viable alternative to traditional barcodes in diverse industries, offering unique advantages despite sharing similar functionalities. Unlike barcodes that require a direct line of sight for scanning, RFID tags can identify objects without this limitation. RFID tags also allow data updates, whereas barcode data is read-only [155, 156]. The reading time of RFID is quicker compared to barcodes [157, 158]. Ultra high-frequency active tags possess a reading range of approximately 100 m with a storage capacity of 1 MB per [2, 26]. However, the need for a power source and higher cost remains significant drawbacks of RFID systems in comparison to barcodes. The evolution of labels, progressing from basic stickers to barcodes and onward to RFID technology, is evident. The increasing utilization of RFID systems aligns with the adoption of the Internet of Things [159]. It would be particularly advantageous if the technology enables wireless transmission of sensor data, encompassing parameters like temperature, movement, and position [160, 161]. This can be achieved through the integration of smart sensors and GPS technology, facilitating the establishment of smartphone-based traceability systems [162–164].

2.5 Evolution of artificial intelligence for food packaging and classification

Since the start of the twenty-first century, IP has rapidly increased, ranking among the world's essential economic endeavors [165]. As economic and technological progress accelerates, advancements in packaging become more crucial to commodity circulation. Such designs not only enhance aesthetic appeal and commodity value but also influence consumer choices and reflect corporate cultural leanings [166]. By integrating AI, this area can achieve greater market sustainability, anticipate upcoming design trends, and optimize product efficiency [167].

In the food processing industry, the organization and packaging of products pose complex challenges, consuming substantial time and effort within manufacturing facilities [168]. Some research shows constructing a fuzzy cognitive map to determine the shelf life of food storage to prevent food losses [169]. Employing AI-based systems to manage these complex tasks minimizes the likelihood of errors and significantly enhances industrial production rates. The complexity arises from variations in the shapes, colours, and sizes of fruits and vegetables, necessitating an extensive dataset for comprehensive AI system training to ensure optimal task performance [170, 171]. Diverse research groups have introduced distinct systems for this purpose, including TOMRA, which excels in sorting with 90% accuracy and expediting production [172]. Presently, automated systems are predominant for product sorting and packaging, supplying industries with benefits such as higher production speed, superior quality yields, and reduced labor costs.

Intelligent decision-making systems that utilize AI encompass a range of tools and methodologies. These include high-resolution cameras, laser technology, X-ray scanning, and IR spectroscopy. These tools work collectively to provide a comprehensive evaluation of food products, particularly fruits and vegetables, when subjected to analysis. Traditional systems predominantly categorize products based on visual attributes. Utilizing TOMRA, notable enhancements of 5–10% in potato sorting have been observed [173, 174]. A similar outcome was achieved by a Japanese company employing a TensorFlow ML-based system, leading to significant benefits within their production unit. These systems have demonstrated exceptional efficacy in diverse food processing industries, with precise performance. The success in potato sorting paves the way for the expansion of AI-based systems into various segments of the food processing industry [168].

2.5.1 Application of artificial intelligence technology in assessing food freshness

The quality of food is closely connected to how fresh it is, and IP plays a key role in keeping it fresh for longer and reducing economic losses from spoiling. To address these concerns and keep up with the increasing need for real-time monitoring of food quality changes, it is imperative to advance the development of effective IP systems. Such IP endeavors not only to enhance the aesthetic appeal of food products and their market value but also to minimize health risks associated with subpar food quality and safety [74]. Nevertheless, the implementation of IP technology for monitoring food freshness is still in its initial stage. Current sensor technology faces limitations in terms of quantity and detection speed, in addition to being costly and sensitive to environmental factors, constraining its utility in SP [168]. To enhance the intelligence and detection capabilities of smart packaging materials, innovative sensors with improved performance are under development [175]. New methods are emerging that combine intelligent packaging materials with AI technology. Researchers are investing more in combining methods for detecting food freshness with AI algorithms [176]. AI technology, based on computer science and focused on data, utilizes expert systems that incorporate mathematical and physical knowledge. These systems encompass various processes including perception, comprehension, logical reasoning, learning, and adaptation [177]. As AI continually advances with the growth of electronic information technology, it finds applications in data analysis, classification, pattern recognition, and other facets essential to the evaluation of food quality and freshness [177].

A modern deep learning approach has been devised to assess olfactory quality across a range of food products, including meat, fish, coffee, alcoholic beverages, mushrooms, cheese, cereals, sugar, and packaging materials. This method focuses on two key indicators: microbial populations on the food's surface and total volatile basic nitrogen. These markers undergo thorough examination using a complex multilayer convolutional neural network (CNN) architecture. CNNs process data through convolutional, pooling, and fully connected layers, employing diverse mathematical techniques to integrate information between input and output layers [179]. The study presented a novel meat freshness monitoring system that merges a cross-reactive colorimetric barcode technique with an advanced deep convolutional neural network (DCNN), recognized for its speed, precision, and non-invasive characteristics. This system benefits both consumers and the wider food distribution network by providing reliable freshness assessment [180]. Khaled et al. introduced a digital classification method utilizing DCNNs to categorize bell peppers into five distinct classes, streamlining the sorting process to align with export standards [181]. Certain studies have explored the integration of the random forest algorithm with artificially generated outliers within genuine samples, offering a novel approach to identifying anomalies associated with food freshness [178, 182].

3 Conclusions

The extensive review regarding modern food technology and its impact on intelligent food packaging emphasizes the crucial role of food packaging in maintaining the quality of products throughout the complex food supply chain. Modern food technology has led to the emergence of intelligent food packaging. This packaging integrates sensors, indicators, data carriers, and AI techniques to maintain a continuous chain of food safety, freshness, and traceability from production to consumption. The review provides an in-depth exploration of the multifaceted components that constitute intelligent food packaging, including time–temperature indicators, gas indicators, freshness and pathogen indicators, as well as a variety of sensors and data carriers. These components work together to ensure the quality and integrity of the packaged products. The growing influence of AI in IP is highlighted, paving the way for more innovative and efficient food packaging solutions.

In addition to the current advancements, future directions in this field offer exciting prospects. The integration of AI into intelligent food packaging is composed to become even more sophisticated, enabling real-time monitoring and decision-making. This opens up an exciting area of possibilities where packaging can adapt and respond to changing environmental conditions and consumer preferences. One of the most compelling future directions is the potential for highly customized packaging solutions that can cater to the unique requirements of specific products. This level of precision promises to significantly reduce food waste and enhance sustainability efforts, aligning with the global movement toward eco-friendly practices and resource conservation. This review serves as a guiding compass through the dynamic world of modern food technology and its deep impact on intelligent food packaging. By examining the integration of AI, it highlights the path toward improved food safety, quality, consumer satisfaction, waste reduction, and enhanced traceability in the food industry. Indeed, intelligent food packaging represents a forward-looking and inventive strategy to address the evolving demands and complexities of the current food supply chain. It is an exciting future that promises to reshape how we perceive, interact with, and benefit from the very packaging that safeguards the sustenance we rely on.

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Declarations

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