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Review

Recent Advances in the Fabrication of Intelligent Packaging for Food Preservation: A Review

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Abstract: The advancement of intelligent packaging technologies has emerged as a pivotal innovation in the food industry, significantly enhancing food safety and preservation. This review explores the latest developments in the fabrication of intelligent packaging, with a focus on applications in food preservation. Intelligent packaging systems, which include sensors, indicators, and RFID technologies, offer the real-time monitoring of food quality and safety by detecting changes in environmental conditions and microbial activity. Innovations in nanotechnology, bio-based materials, and smart polymers have led to the development of eco-friendly and highly responsive packaging solutions. This review underscores the role of active and intelligent packaging components—such as oxygen scavengers, freshness indicators, and antimicrobial agents in extending shelf life and ensuring product integrity. Moreover, it highlights the transformative potential of intelligent packaging in food preservation through the examination of recent case studies. Finally, this review provides a comprehensive overview of current trends, challenges, and potential future directions in this rapidly evolving field.

Keywords: food security; food preservation; intelligent packaging; sustainability; environmentally friendly

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1. Introduction

The need for sustainable food sources has become critical globally, underscored by rising hunger rates. In 2017, 83 million people across 45 countries faced starvation (World Bank) [1], and hunger has since worsened; in 2023, around 733 million people experienced hunger (SOFI) [2] (G20 Task Force, 4) [1]. Factors like climate change, economic crises, and conflicts drive this increase, with projections indicating that 582 million individuals may still be affected by hunger by 2030 (World Food Programme, United Nations) [2,3]. Efforts to meet food demand, intensified by population growth, are hindered by inefficiencies, with about 14% of global food wasted between harvest and sale, especially fruits and vegetables (FAO) [4]. Addressing this wastage through the integration of advanced food science and technology is essential to improving food security and sustainability [5].

Over the years, food preservation has been a major concern due to food spoilage, leading to continued efforts directed toward extending shelf life, reducing waste, and ensuring safety. This has resulted in the development of several preservation technologies associated with addressing this challenge. Some of these technologies include drying [6–8], heating [9,10], freezing [11–13], high-pressure processing to delay microbial growth [14–16],

and fermentation to regulate pH levels [17]. In recent years, however, technologies such as food packaging for shelf-life extension have emerged to ensure that food quality during production, storage, and marketing is maintained while preventing environmental damage [18,19]. Thus, the fundamental functions of food packaging have been dubbed to primarily serve the purpose of containment, communication, security, convenience, and responsible disposal. These responsibilities are essential for safeguarding food quality and enhancing marketability and consumer satisfaction [20]. Given that maintaining product quality constitutes the paramount consideration throughout the entire supply chain [21], ensuring the quality of packaged food is the primary objective of packaging. While traditional packaging methods are well established in the food industry, they primarily address issues related to protection from external causes [21]. Nevertheless, the traditional packaging approaches have been, in recent times, found to be inadequate in preventing spoilage and extending shelf life due to the complexities associated with fast-moving consumer goods, which include regulatory compliance, market dynamics, extended shelf lives, accessibility, environmental impact, product integrity, and significant concerns regarding food waste [22].

Consequently, intelligent packaging has emerged as a significant advancement, enhancing food safety and enabling the real-time monitoring of food quality across the supply chain [23]. A key feature is its capacity to inform consumers about product conditions during storage and transportation [24–26], typically through assessing food decomposition via oxidation or reduction levels [24]. Since products may deteriorate before expiration dates, effective quality management is essential for consumer safety and industry efficiency. Intelligent packaging helps address factors such as temperature fluctuations, microbial spoilage, package integrity, and freshness, thereby minimizing food waste, reducing foodborne illness risk, and improving traceability [27,28]. This technology holds substantial commercial potential by reducing food loss and mitigating risks like allergic reactions and contamination [23].

Therefore, this review aims to provide an overview of the latest advances in the fabrication of intelligent packaging systems, with a focus on their application in food preservation. Additionally, it explores current technologies implemented in intelligent packaging while also, in brief, exploring the latest advancements in materials used for intelligent packaging, highlighting their benefits in reducing food waste and enhancing consumer confidence regarding product quality and safety. Furthermore, several case studies are presented to illustrate successful applications across various food categories, thereby emphasizing the practical implications and effectiveness of these technological advancements.

2. Brief Background and Types of Food Packaging Systems

Food packaging has progressed significantly from natural materials like animal hides, leaves, and shells [29] to early ceramic and glass containers for storage and contamination prevention [30–32]. The growing food industry and the demand for fresher and more nutritious products have reduced reliance on these traditional methods [33,34]. In recent years, several new techniques have emerged, including coatings, antimicrobial packaging, antioxidant packaging, and modified atmosphere packaging (MAP) [21]. Conversely, intelligent packaging is a recently introduced approach in the food packaging industry that safeguards the food and informs customers about the environmental status of the packaged food [21]. It is important to recognize that the concept of intelligent packaging is closely connected to active packaging. Active packaging (AP) is a specialized system intended to actively interact with the food contents it encloses, thereby enhancing the shelf life and quality of food substances [35]. It focuses mainly on performing additional functions beyond the passive role of simply containing and protecting the food, while

intelligent packaging focuses on the capability to detect or monitor specific attributes of the food product, the internal package environment, or the shipping conditions [21]. Additionally, users may receive information from intelligent packaging, or it may initiate active packaging operations. Several reviews have been conducted on active and intelligent packaging [36–40].

3. Intelligent Packaging

Intelligent packaging encompasses packaging technologies that integrate functionalities specifically intended to monitor, communicate, or enhance various aspects pertaining to the state, caliber, or security of the product being packaged. According to Vanderroost et al. [41], intelligent packaging is a comprehensive packaging solution that intelligently monitors alterations in a product or its surroundings and actively responds to these changes [41]. Intelligent packaging employs chemical sensors or biosensors to oversee the quality and safety of food throughout the entire journey from producers to consumers [42]. Intelligent packaging further employs a range of sensors to oversee the quality and safety of food for identifying and examining properties such as freshness, pH levels, carbon dioxide, pathogens, oxygen, and leaks, as well as monitoring time and temperature [43]. The specific features of intelligent packaging solutions differ depending on the enclosed product [42]. Similarly, the specific condition that needs to be observed, communicated, or modified also differs accordingly. Nevertheless, intelligent packaging enables the monitoring and tracing of a product throughout its entire life cycle by providing the platform to analyze and manage the internal or external environment of the package, offering real-time information on the product's condition to manufacturers, retailers, or consumers [43]. The following are examples of devices or sensors commonly employed in intelligent packaging to monitor the quality and safety of food items.

3.1. Time–Temperature Indicators (TTIs)

These are devices used to monitor the temperature of products within a package [44]. Temperature determines how long a particular food item may be stored [40]. Maintaining the nutritional value of food while shielding it from undesirable temperature changes remains one of the biggest concerns and challenging tasks for perishable foods [45]. Inadequate or unregulated temperature regulation may result in significant food loss during procurement and the supply chain [45]. According to research studies, improper temperature control in transporting and storing perishable foods can result in a 35% loss of product [46]. Time–temperature indicators offer crucial assistance in addressing this concern. Time–temperature indicators detect the surroundings around a package and use that information to detect changes in temperature [47]. It is also useful for detecting time-and-temperature-dependent enzymatic and microbial changes in food products [48]. Temperature-sensitive items, especially refrigerated and frozen goods, are primarily used for time–temperature indicators [45]. They are additionally used to regulate pasteurization and sterilizing processes [49]. The categorization of TTIs differs slightly between authors, with the most straightforward division into two groups being partial or comprehensive history indicators [45]. A partial history indicator only activates if a specific preset temperature limit is surpassed, signaling potentially harmful temperature levels, which could lead to microbial survival and protein damage during freezing [18,50]. To offer a measurement throughout the lifespan of the item, an in-depth historical indicator continually reacts to all temperatures across the food distribution chain [45,51,52]. Due to their fundamental properties, TTIs are regarded as easy-to-use and readily reachable tools. The various classifications of TTIs are summarized in Figure 1.

However, despite this, the implementation of TTIs beyond their practical applications has been described as a complex task [53–55] These studies indicate that an appropriate response to temperature fluctuations and adherence to the product's spoilage kinetics are essential for the effective use of TTIs in real-world applications. Extensive pilot studies or consistent applications within actual distribution chains are uncommon [55]. Although the potential of TTIs to significantly enhance cold chain management has been acknowledged, their practical adoption has frequently been hindered by concerns regarding the lack of industry engagement, liability challenges, legislative uncertainties, and toxicity [18,21,56,57]. However, recent conversations about food waste once again highlighted the significant potential of intelligent packaging [53,58]. Immediate action is thus essential, particularly for environmentally sensitive products like meat, which have a significant impact during production [58,59]. Due to frequent reports of discrepancies between the printed best-before date and the actual condition of the product [59], the use of TTIs provides a way to track individual items and incorporate a dynamic shelf-life system for the product [60]. In addition to precise temperature monitoring, properly evaluating the remaining shelf life based on the color changes in TTIs is crucial for ensuring the delivery of high-quality, safe products and minimizing food waste. In addition to aligning food properties with TTIs kinetics, the practical application of the information provided by the TTIs plays a crucial role in companies' decision-making processes. Therefore, to determine the precise caution and action control ranges at specified inspection points based on the label's color change, models are necessary [55].

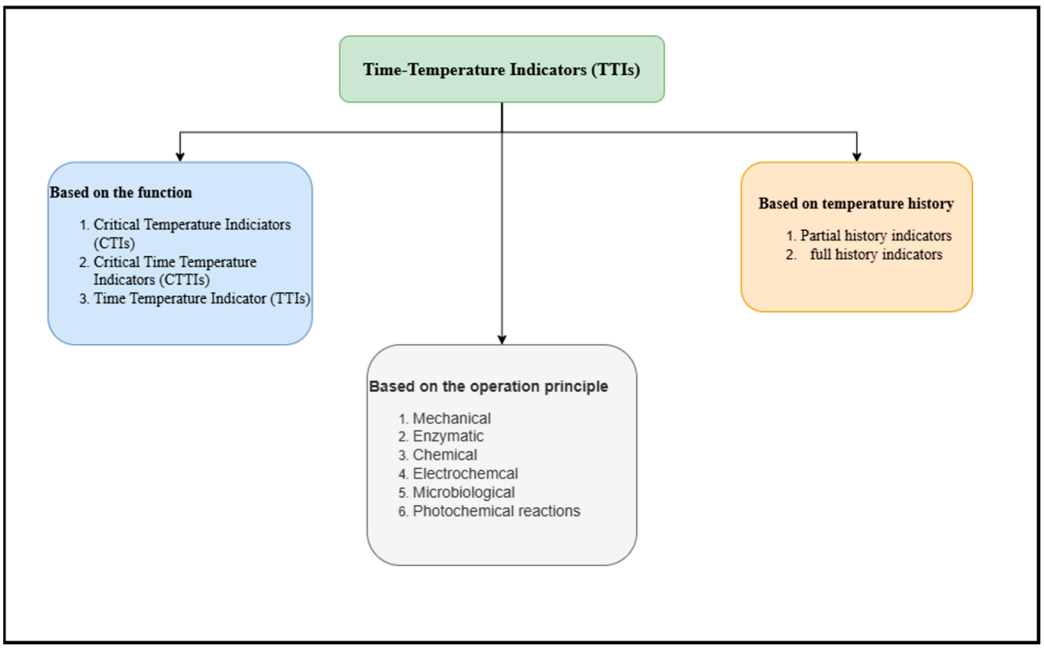


Figure 1. Classification of time–temperature indicators (TTIs) [47]. Reproduced with permission from J Food Process Technol, under the terms of the Creative Commons Attribution License (Copyright, 2021).

Furthermore, Table 1 summarizes various principles and applications of some currently used TTIs in the market. This table also shows a variety of principles, primarily involving a physical shift or chemical action, which include polymerization, melting, or acid-based reactions, typically manifest as an observable reaction by mechanical distortion or color change [45].

Table 1. Some of the time–temperature (TTIs) indicators obtainable commercially [45]. Reproduced with permission from MDPI, under the terms of the Creative Commons Attribution License (Copyright, 2020).

Company Name	Application	Principle	Website
3M™ MonitorMark®	Bakery, drinks, and meat	Monitors temperature sensitivity rather than the quality of the item via an adhesive-based pad that is simple to affix to secondary containers. The pad contains esters of blue fatty acid within a carrier material. Once the carrier experiences a phase shift because of exposure to temperatures exceeding the reaction temperature, the dye stays within the pad; consequently, as the dye disperses across a wick, the reaction is calculated based on how far the dye traveled down the track.	(www.3m.com)
OnVu™	Milk products, meat, and fish.	It is made of photochromic ink that operates on benzylpyridines that are turned dark blue under ultraviolet (UV) light. Then, irrespective of the outside temperature increases, benzylpyridines gradually become lighter as time passes.	(www.packworld.com)
WarmMark®	Transportation, storage, and processing	Clear evidence of temperature fluctuations that resulted in a pass or fail. It consists of a pad of blotting paper that was colored red.	(www.deltatrak.com)
OliTec™	Fresh goods	It has multiple layers and can track the deterioration patterns of food items under storage circumstances.	(www.oli-tec.com)
Cold Chain iToken™	Supply chain	Barcode scanners can detect the positive “ON” signal from an easy pull-tab operation.	(www.deltatrak.com)
Insignia Deli Intelligent Labels™	Chilled goods	The rate of hue shift increases as the pre-calibrated temperature setting shifts or fluctuates.	(www.insigniatechnologies.com)
TOPCRYO	Cold chain	Device can track whether the cold chain is being followed, and the microbial label turns red from green.	(www.cryolog.com)
TempDot®	Meat and seafood	The indicator window, which validates activation, allows the labels to be sent and kept at any temperature.	(www.deltatrak.com)
Smart dot	Frozen goods and bakery items	When subjected to heat, the indicator turns from green to red.	(www.evigence.com)

Table 1. *Cont.*

Company Name	Application	Principle	Website
FreshCode®	Chicken products	The indicator's white core has smart ink embedded in it. This records the release of flammable gases made when chicken is spoiled in packing with the changed environment.	(www.freshcodelabel.com)

3.2. Freshness Indicators

Freshness indicators are innovative tools designed to monitor and communicate the quality of food products during storage and transportation by detecting microbial growth and chemical changes. These indicators, embedded within the packaging, interact with by-products of microbial activity, providing visual cues about the product's microbial quality [61,62]. For instance, the FreshTag® colorimetric indicator labels, introduced by COX Technologies in 1999, responded to volatile amines produced during seafood storage but were discontinued in 2004 [40,63]. Similarly, Yoshida et al. developed a bio-based pH indicator using chitosan to detect metabolites like *n*-butyrate and lactic acid [64]. Indicators such as those developed at Sejong University, which use whey protein isolate or chitosan solutions, detect carbon dioxide accumulation in meat and poultry through changes in transparency due to pH shifts [65]. While these innovations provide direct insights into food quality by analyzing degradation processes caused by microbial growth, challenges remain, such as false positives from color changes unrelated to actual quality decline [63,65–67]. Freshness indicators, unlike temperature indicators, assess decomposition onsets by monitoring target compounds like amines, oxygen, and carbon dioxide. Despite their application in fresh produce, fruits, and fish, their adoption, particularly in Europe, remains limited due to legal concerns about potential food-contact compounds. Unlike temperature indicators, freshness indicators provide direct data on the condition of the item by examining the chemical processes involved in food degradation caused by target microbes [68]. With various smart packaging innovations, the quality of the product can be determined and communicated. In most cases, freshness indicators rely on the use of dyes that are sensitive to pH variations resulting from the deterioration of the product, leading to a visible change in the color of the indicator [45,69,70]. These indicators have been utilized in various items, such as fresh produce, fruits, and fish. Some examples of freshness indicators available on the market, along with principles of operation, are provided in Table 2.

Different polymeric substrates have been coated with pH-sensitive pigments such as bromophenol blue, methyl red, cresol red, bromocresol purple, and bromocresol green [45]. Organic colorants like curcumin, grape peel, and beetroot extracts have also been studied for their ability to detect the deterioration of cod meat [71]. Alternatively, the nutritional value of meat products can be assessed using hydrogen sulfide indicators [36,45]. Hydrogen sulfide is particularly associated with the pigmentation of myoglobin, which is considered a quality trait for meat products [36]. For fish deterioration, a method utilizing corn starch, chitosan, and red cabbage juice was tested [72]. Nevertheless, freshness indices for seafood are based on volatile amines, which are introduced as the food deteriorates [73,74]. Most sensing techniques rely on color-changing pigments, but incorporating dye into the packaging can alter the sensory characteristics of the product [45]. However, scientists have developed freshness indicators consisting of three layers: an outer layer made of low-density polyethylene, a layer made of non-woven high-density polyethylene, and a

layer containing bromocresol green, a pigment highly responsive to pH changes. Freshness markers are either printed on the wrapping material or directly integrated into the material as tags, and they respond to the substances generated during storage [75].

Table 2. Freshness indicators that are obtainable conventionally [45]. Reproduced with permission from MDPI, under the terms of the Creative Commons Attribution License (Copyright, 2020).

Commercial Identifier	Application	Principle	Description of How They Function	Website
Raflatac	Poultry	It works by breaking down cysteine within a hydrogen sulfide reaction using a nanolayer comprising silver or silver nanoparticles.	During the packaging, the indication appears opaque light brown; however, as silver sulfide forms, the coating's color changes to translucent.	(www.upmraflatac.com)
Food fresh™	Meat	It consists of an irreversible duration tracking self-adhesive label indicator that may be programmed to expire after a specified "consume within" period of time, which can be anything from just a couple of days to several months.	A permeable barrier is present within the indicator, whereby a colored liquid moves at a predetermined speed.	(www.vanprob.com)
RipeSense®	Fruit	It can identify gases or fragrance compounds that are part of ripening, such as ethylene.	The label starts off red, changes to orange, and then to yellow when the fruit ripens.	(www.ripesense.co.nz)

3.3. Biosensors and Gas Sensors

Biosensors are used to detect changes in food packaging caused by biological processes [47]. The two main components of biosensors are bioreceptors and transducers [28]. The bioreceptor recognizes the bio-enzymatic component, which is then transformed into measurable electrical output by the transducer. Biosensors can detect allergens, glucose, carbohydrates, amino acids, alcohols, fatty acids, pathogenic organisms, and other analytes [41]. They can also detect target metabolites produced during the decomposition of food [76]. One key challenge with these sensors is immobilizing biological materials within the receptor to prevent denaturation and disintegration, often achieved through adhesive techniques like electro-deposition [45]. It is crucial to avoid any harmful consequences from biological constituents migrating onto food [41,77]. The transducer can be electrochemical or optical [78]. Among the various biosensors discussed in the literature, those with electrochemical sensors have been the most extensively researched [45]. The chemical composition of gases in the packaging's atmosphere changes due to the food, packaging construction, and external factors when the package is exposed [79]. This poses a challenge in maintaining the nutritional value of food ingredients within the packaging chain. Gas indicators have thus been developed to address this challenge ck the shifts in gases and to assess the performance of active packaging elements like carbon dioxide and oxygen scavengers [18]. Oxygen, which causes the degradation of nutritional quality through microbiological and biochemical processes, is removed from the packaging, and replaced with inert gases such as nitrogen. Additionally, oxygen scavengers, typically solid materials incorporated into packaging, can be used to further reduce residual oxygen levels,

thereby enhancing the shelf life of food products. This is especially important for products preserved in MAP (modified atmosphere packaging) [80]. The most used gas indicators are employed to control the levels of both carbon dioxide and oxygen [81]. Oxygen, which causes the degradation of nutrition through microbiological and biochemical processes, is removed from the packaging and replaced with other gases like nitrogen or oxygen scavengers [82]. Hence, it is essential to use a visual oxygen indicator to confirm the presence of oxygen quickly and easily in the package without the need for specialized machinery or laboratory testing [83]. A widely used oxygen indicator is a colorimetric indicator that relies on the reaction of an alkaline solution (sodium or potassium hydroxide) with a redox dye (typically methylene blue) and a reducing agent (glucose) [42,83]. The second most common category of gas sensors relates to CO_2 [45]. Microbes that cause food to deteriorate begin proliferating as soon as it is packaged. Due to the metabolic processes of bacteria, CO_2 is produced e type of food, the length of preservation, storage conditions, and packaging style, all impact the level of carbon dioxide formation [84]. Furthermore, carbon dioxide, nitrogen, and oxygen are used in protective atmospheric technology to slow down the metabolism of microbes [85]. Most carbon dioxide sensors include colorimetric labels, which vary in color based on the pH of the food being sold. For example, Saliu et al. [86] conducted a study on the effectiveness of a colorimetric indicator composed of red cabbage lysine, polylysine, and anthocyanins. Anthocyanins have gained attention from researchers investigating their role as organic pigments in combination with organic compounds, with the goal of developing safe, environmentally friendly, biodegradable colorimetric indicators for the food industry [87–89]. Gas sensors are commonly sold as labels, tablets, printed layers, or coated in polymer films, providing a means to assess the nutritional value and safety of edible products [79]. Some commercially available gas sensors, their applications, and their purpose in some currently available intelligent packaging materials in the food industry are summarized in Table 3.

Table 3. Gas sensors that are obtainable commercially are used in intelligent packaging for food [21].

Commercial Name	Application	Purpose	Indicating Point	References
Ageless Eye®	Meat	Monitoring oxygen gas.	Transition from pink to a blue hue or purple.	[21,42,56]
Tell-Tab™	All products	Identifying oxygen gas inside the packaging.	Transition from pink to blue or purple.	[40,51]
Shelf Life Guard	Meat	Monitoring of air in the package surroundings.	Transition from colorless to blue.	[18]

4. Current Fabrication Approaches for Intelligent Packaging

Current fabrication approaches for intelligent packaging utilize a combination of advanced material science and state-of-the-art manufacturing techniques. These approaches aim to transform the packaging, monitoring, and preservation of products. Intelligent packaging materials thus encompass the use of a wide range of innovative approaches, including nanotechnology, microfluidics, 3D printing, and the application of electromagnetic methods [21]. These fabrication technologies signify a paradigm shift towards more sustainable, efficient, intelligent packaging solutions poised to reshape various sectors, including food, pharmaceuticals, and consumer goods. For example, nanotechnology is transforming food packaging by integrating nanoparticles into polymer matrices. This enhances barrier strength, extends product shelf life, and provides antimicrobial protection [90]. Specifically, metal-based nanoparticles, such as silver, have been well documented for their ability to actively prevent bacterial growth. Additionally, some of these materials function as

nanosensors, capable of detecting spoilage gases and maintaining food safety [91]. Microfluidics, another groundbreaking technology, incorporates miniature fluid channels into packaging, enabling the detection and response to environmental changes such as pH or temperature fluctuations [92]. This real-time monitoring capability is critical for preserving the quality of perishable products. Similarly, 3D printing offers remarkable flexibility in packaging design, allowing for the creation of customized, smart packaging with integrated sensors and innovative structural elements. This approach enhances packaging performance and minimizes material usage [93]. The use of electromagnetic techniques, including radio-frequency identification (RFID), is also becoming increasingly popular [94]. These technologies enable wireless monitoring, data transmission, and seamless interaction between packaging and consumers' smart devices, enhancing supply chain visibility and boosting consumer involvement [95]. Together, these advanced technologies are evolving intelligent packaging from a passive storage solution into an active, responsive, and interactive system that boosts food safety, minimizes waste, and promotes greater sustainability.

4.1. Nanotechnology

Nanotechnology has recently become a critical tool in the development of antimicrobial coatings and barrier films, significantly enhancing the protective properties of packaging materials [96]. This technological advancement is particularly important in food packaging because it extends the shelf life of products and improves the safety, texture, taste, appearance, and nutritional content of the food [97]. As a result, the integration of nanotechnology into active and intelligent packaging systems provides substantial benefits for food shipment, preservation, and overall packaging efficiency [97]. Compared to conventional food packaging materials, nanotechnology-based solutions offer superior advantages regarding confinement, convenience, safety, food preservation, and consumer interaction [98]. However, before these materials can be widely adopted, it is crucial to fully understand their composition, environmental impact, safety, and potential toxicity [97]. Recent research has addressed these concerns by examining the regulatory and toxicological challenges, migration issues, sustainability considerations, and various applications of nanotechnology in food packaging [99,100]. The impact of nanoparticles in packaging is largely determined by their physicochemical properties, such as size, shape, crystallinity, distribution state, and surface characteristics [101]. In food packaging, both inorganic nanoparticles, such as transitional metals (e.g., copper, silver, gold), alkaline earth metals, non-metals (e.g., selenium, silicates), metal oxides (e.g., zinc oxide, silicon dioxide, titanium dioxide), and organic nanoparticles, like cellulose nanofibers, are being increasingly utilized [102]. Naturally occurring organic nanomaterials, such as starch, nanocellulose, and chitosan, are being employed due to their biodegradability and effectiveness in enhancing the functional properties of food packaging [97,103].

Additionally, nanoparticles are utilized in various forms, such as nanotubes, nanoliposomes, nanofibers, nanoemulsions, nanospheres, and nanocomposites within the food sector [101]. Since the viability of nanotechnology as a valuable additive in material science for food technology was recognized, extensive research has been conducted to explore its applications. Nanotechnology has revolutionized conventional food packaging by transforming it into active and intelligent packaging, offering benefits beyond merely protecting the product and displaying the brand [102]. For instance, Enescu et al. [102] demonstrated that the incorporation of nanoparticles such as nanoclays, zinc oxide (ZnO), and titanium dioxide (TiO_2) significantly improve moisture regulation in absorbent pads used to soak up liquids from meat, poultry, and fish placed in display packaging trays. Moreover, nanoparticles enhance antioxidant capabilities in packaging components, such as small sachets that trap residual oxygen or ethylene within the package. This reduction in oxygen

exposure helps prevent microbial growth and chemical changes in the food, thus extending its shelf life. Nanotechnology also contributes to the development of lighter packaging materials that remain environmentally friendly [104].

Bio-nanocomposite films also incorporate advanced nanomaterials such as nanowires, nanofibers, nanoplatelets, and nanotubes [97]. These materials enhance the mechanical and barrier properties and exhibit intelligent packaging characteristics by actively monitoring and controlling the food environment within the sealed package [105]. Various nano-based food packaging materials currently in use, which have been approved and commercially adopted, are summarized in Table 4.

Table 4. Examples of commercially accessible nanotechnology-based material used in intelligent packaging along with their respective functionalities [96,106].

Type of Material	Company and Brand	Form	Utilization Product	Function
Cerium oxide	Mitsubishi Gas Chiyoda-ku, Japan Chemical Inc., OMAC® Imperm®.	Film	Produce responses and hot-fill fish and meat items	O_2 scavenger
Iron oxidation	Clariant Ltd., Swaziland, Mutten, OxyGuard®.	Film and sachets	Snacks that are fried	O_2 scavenger
Time–temperature indicator (TTIs) based on Ph-indicating dye, lipase, and enzyme	Mitsubishi Gas Chemical Inc., Japan, Chiyoda-ku, Ageless®.	Stickers	Eggplant, strawberries	CO_2 scavenger
Nanoencapsulation (titanium dioxide)	Carnation Breakfast Essential, Switzerland, Vevey, Carnation Instant Food.	Powder	Milk-based goods in powder form	Anticaking
Composite of nylon 6-nanoclay	Honeywell International Inc., USA, Phoenix, AZ, Aegis HFX Resin and OXCE Resin.	Nylon resin barriers	PET bottles containing beer and flavored alcoholic beverages	O_2 scavenger
Nanosilver	Addmaster Limited, USA, Monrovia, CA, Biomaster.	Spray and bag	Vegetables and fruits	Antimicrobial properties
Adjusting color in response to aromatic chemicals (sensor)	Ripesense Limited, New Zealand, Tauranga, RipeSense™.	Stickers	Fruits	Freshness indicators

The intelligent packaging market is anticipated to experience rapid growth in the coming years, driven by its unique, interactive, and cost-effective features that appeal to consumers [106]. In 2023, the global intelligent packaging market was valued at approximately USD 23.6 billion and is projected to grow to USD 56.0 billion by 2033, with a compound annual growth rate (CAGR) of 9.0% over the forecast period [107]. This growth, primarily driven by the increasing use of active and interactive packaging technologies, is projected to capture approximately 72% of the market share in the coming decade. The global smart packaging market is expected to increase from USD 24.66 billion in 2024 to

USD 40.02 billion by 2032, reflecting a compound annual growth rate (CAGR) of 6.24%, highlighting the strong growth of the industry [108]. The distinctive advantages of intelligent packaging, including enhanced product safety and real-time monitoring capabilities, position it as a key innovation in the evolving landscape of food technology. As a result, this sector is expected to expand significantly, offering new opportunities for manufacturers and consumers.

4.1.1. Nanocomposite Compounds for Improved Barrier Properties

Nanocomposite materials have emerged as an innovative remedy for augmenting barrier characteristics across diverse materials, especially within the food packaging industry [109]. The barrier property of a nanocomposite polymer or film is typically determined by its ability to allow or restrict the passage of water vapor and oxygen [110]. Nanocomposites comprise a polymer matrix strengthened by particles within the nanometer scale in at least one dimension (nanoparticles) [111]. Additionally, these materials demonstrate significantly enhanced characteristics due to the nanoparticles' high aspect ratio and extensive surface area [111]. Presently, prominent nanocomposite food packaging incorporates materials like silver nanoparticles, zeolites, zinc oxide nanoparticles, and nano clay [110]. Clay minerals can be added to biopolymers to boost their strength and resistance properties while preserving their ability to break down naturally [111]. The enhanced characteristics of biopolymer-based nanocomposites offer the potential to substitute traditional packaging materials like plastics. Furthermore, the enhancement in polymer nanocomposite barrier properties is commonly described in the literature as resulting from greater tortuosity due to the introduction of fillers, as illustrated in Figure 2 [112].

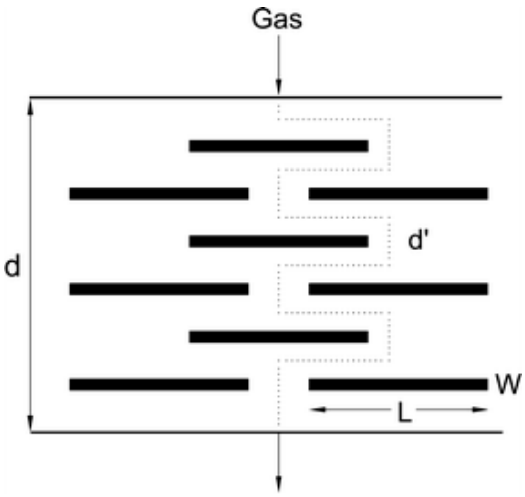


Figure 2. The uses of nanocomposites in food packaging [113]. Reproduced with permission from Springer, copyright (2024).

The more tortuous the diffusive channel for permeable substances, the better the barrier characteristics of polymer–clay nanocomposites (Figure 2). As a result, they are forced to take a longer route to disperse across the picture. Higher aspect ratios of nanoparticles reduce the degree to which gases, including carbon dioxide, water, and oxygen vapor penetrate food packaging, which is relevant to food packaging [113]. This notion was created by Nielsen [112] and subsequently backed by additional researchers [114,115]. The clay's proportions and the filler's percentage of volume within the composite impact the rise in overall path length. During clay load values below 1%, Nielsen's model can be employed to estimate the porosity of systems, although a few experiments have demonstrated that permeability at greater loadings is significantly lower than expected [113,114].

By emphasizing the polymer–clay barrier as a further regulating component of the tortuous route, Beall [116] offered a novel approach for estimating the porosity of nanocomposites, offering an improvement to Nielsen's model. A less limiting channel for gas entry existed within the microstructure of traditional composites [117]. According to a literature report, innovative PET nanocomposites demonstrated improved barrier characteristics against water and oxygen [118]. Adding multilayer silicates enhanced the barrier qualities of maize zein nanocomposite covered polypropylene films in food-related packaging [119]. As opposed to plain starch films, the water vapor porosity of starch–clay nanocomposites have also been improved [118–121].

4.1.2. Nanosensors

Nanosensors are tiny devices that can attach to anything that has to be sensed and then transmit back a signal [122]. These nanosensors have the capacity to recognize and react to physical, biological, and chemical signals, converting their response to a signal or result that individuals can utilize [122]. The nanoscale transformation may bring about significant advancements in alimentary packaging, including disease detection, mechanical qualities, and cutting-edge packaging solutions that guarantee the security as well as the quality of food [122]. Many nanosensors have been invented to detect interior and exterior parameters within alimentary packaging [123]. According to Joyner et al. [124], nanosensors can be utilized to detect bacteria, toxins, pollutants, and food freshness. Additionally, nanosensors could be created to regulate both the internal and external environments of food items [125]. Numerous studies have been carried out in this area, even though chemosensors made from nanoelements are not yet commercially viable [126]. Additionally, there are numerous effective examples of nanosensors that can detect food rotting signs with high sensitivity. Conjugated polymeric nanocomposites were examined by Pavase et al. [127] for use in the development of colorimetric along with fluorimetric food sector sensors. Radio-frequency identification (RFID) tags are among the potential applications that printed electronic devices have brought to intelligent packaging, according to Liao et al [128]. The processes of synthesizing, sintering, printing, and stabilizing printable conductive nanomaterials, such as metal nanoparticles (Ag, Au and Cu) including carbon-based nanomaterials (graphene, CNT), were described [128]. Bumbudsanpharoke et al. [129] concentrated on the difficulties in using nanomaterials in intelligent packaging as well as the latest developments in colorimetric nanosensor technology. The effectiveness and adaptability of metallic nanoparticles, photonic crystal nanostructures, and metal oxide nanoparticles as visual indicators were investigated [129].

4.2. Three-Dimensional Printing

Three-dimensional printing, also known as additive manufacturing, is a promising approach for creating intelligent packaging solutions due to its versatility, speed, and ability to rapidly produce complex structures [130]. This technology allows for the fabrication of customized packaging designs tailored to specific products, enhancing functionality and aesthetics. By integrating sensors, circuits, and other electronic components directly into the packaging material during the printing process, 3D printing enables the creation of intelligent packaging capable of monitoring various parameters such as temperature, humidity, and gas composition in real time [93]. One of the key advantages of 3D printing in intelligent packaging is its potential for rapid prototyping and iteration [131]. Design modifications can be quickly implemented without the need for costly tooling changes, allowing for accelerated development cycles and faster time-to-market [132]. Additionally, by incorporating a function that varies progressively in reaction to an external stimulus, four-dimensional printing expands the potential applications of 3D printing. A common

instance of this kind of feature would be a pigment shift, which is typical of intelligent packaging designs. Many plant colors, like anthocyanins, are highly responsive to pH variations and can reveal information about the condition of the packaged food by changing color, making them ideal to be used as indicators to determine freshness.

Li et al. [133] employed a cylindrical injector and the FDM 3D printing technique, preparing a printed dual-purpose film using chitosan that contains anthocyanins to indicate freshness through color shifts along with the essential oil of lemon grass with antibacterial and antioxidant qualities. The films were able to monitor the spoilage of pigs by shifting the film hue from purple to gray-blue when the pH rose beyond 6, making it possible to visually identify pig deterioration with a smartphone device that measures color [133]. To enhance the shelf life of food, prevent food from spoiling, and provide information on freshness, Zhou et al. [134] created a label that serves two purposes. Anthocyanins were added in the informative portion, which served as a colorimetric indicator of pH variations; 1-methylcyclopropene, an ethylene receptor inhibitor that prevents fruit from ripening and spoiling, was included in the food preservation portion [134]. The packaging purpose determined the selection of various printing conditions. Uniaxial printing was used to generate aerogels for the 3D-printed cushioning packaging [134]. This approach demonstrated strong resilience along with cushioning capabilities, with an average compressive durability rate of over 90% [134].

Recently, studies such as those by Zhai et al. [135] developed a hydrogel-in-oleogel bigel system incorporating anthocyanins extracted from sweet potatoes. In this system, the outer oleogel phase consisted of sunflower oil, beeswax, and glyceride monooleate. Using 3D printing technology, the bigel was applied to a polyvinylidene fluoride (PVDF) film to create a composite material. This bigel effectively prevented anthocyanin leaching, demonstrated sensitivity to trimethylamine (TMA) with a detection limit of 2.52 μM, and monitored meat and salmon freshness through visible color changes during in situ analysis. The study introduced an innovative approach to creating anthocyanin-based colorimetric gas sensors for smart food packaging applications [135]. Similarly, Chaiya et al. [136] conducted a study developing a biodegradable substrate with a colorimetric humidity indicator to detect moisture in food packaging. The substrate was made from a blend of poly(lactic acid) (PLA) and non-toxic poly(ethylene oxide) (PEO). Using solvent-cast 3D printing, they fabricated three-dimensional (3D) substrates, onto which a cobalt chloride ($CoCl_2$) solution was applied via inkjet printing to function as a humidity-sensitive color indicator. The study found that incorporating PEO improved the flexibility and thermal stability of PLA while increasing its hydrophilicity. Additionally, the $CoCl_2$ indicator exhibited a color shift from blue to pink under ambient conditions when relative humidity exceeded 60%, demonstrating its potential for frozen food packaging applications to monitor moisture levels [136].

Additionally, 3D printing enables lightweight yet durable packaging solutions, reducing material waste and transportation costs while improving sustainability [137,138]. Moreover, 3D printing facilitates the integration of novel materials and functionalities into packaging designs. For example, researchers have explored the use of conductive inks and flexible substrates in 3D-printed packaging to create interactive and responsive packaging solutions [137]. Furthermore, advancements in bio-based and biodegradable 3D printing materials offer opportunities to develop eco-friendly packaging alternatives that align with growing consumer demand for sustainable packaging solutions [139]. In summary, 3D printing presents a compelling approach for the fabrication of intelligent packaging, offering flexibility, customization, and sustainability advantages. Continued research and innovation in this field hold the potential to unlock new possibilities for enhancing product safety, shelf life, and consumer engagement through intelligent packaging solutions. How-

ever, understanding the behavior of materials during the food printing process remains a challenge due to the complex nature of food, which exhibits diverse variations in its physicochemical properties [140].

Another challenge includes ingredient blending, material stability during printing, and post-printing variables, as the 3D food printing process relies more on operational parameters than operator skill. As a result, it is crucial to consider the optimization of certain parameters, including ingredient selection, mechanical force, and material formulation. Additionally, as technology and its applications expand, the piracy of digital recipes will pose a significant challenge. Therefore, the necessity of developing new policies to address intellectual property rights and combat piracy is undeniable [141]. Printing speed is another major constraint hindering the commercialization of 3D printing in the food industry [140]. Limited production capacities pose a challenge for large-scale manufacturing. Even in single-unit printing, a typical additive manufacturing (AM) process produces approximately a 1.5-inch component on average. Safety will emerge as an additional concern in large-scale production. To date, no industrial-scale printer has been developed [142]. Creating printers that are cost-effective, highly reliable, and capable of rapid production continues to be a significant challenge. Oropallo et al. [143] described a comprehensive viewpoint on the challenges related to 3D printing technologies, emphasizing the necessity for further in-depth research.

4.3. Microfluidics

Microfluidics is an advanced technique for regulating the flow of fluids through channels ranging from 1 to 100 micrometers in diameter [144]. A microfluidic device contains fluid and has numerous channels ranging from nanometers to microns [145]. These tiny channels give the fluid, unique properties that allow various applications in various industries, as shown in Figure 3 [146,147]. Recently, there has been a significant focus on microfluidic technology due to (a) affordable construction expenses and versatility in mass production, (b) potential uses for overseeing physical, biological and chemical processes, (c) the ability to conduct analyses at a high throughput rate, offering potential for the simultaneous detection of multiple elements and practical parallelization, (d) the utilization of smaller quantities of reagents and samples, usually less than 1 μL, which results in a decrease in analysis expenses and the generation of waste, (e) the ease of use, and (f) disposability [148–151]. The food industry is one of the industries where microfluidics has shown great potential. Microfluidic techniques can create nanoparticles and fibers in a variety of shapes [152]. Microfilms can be used as functional food packaging, and microfibers created through microfluidic spinning can be used in tiny reactors for evaluating chemical elements [153,154]. Droplet-based microfluidics is a cutting-edge technique for producing particles in a controlled manner [155]. This method can create stable emulsions that are commonly used in food processing by carefully regulating channel barriers [156]. The droplet-based microfluidic technique also produces improved particles that facilitate the encapsulation and dispersion of active ingredients [157].

A couple of the most recent and exciting ways that microfluidic technologies are being used to evaluate the quality, and the security of food are listed in Table 5.

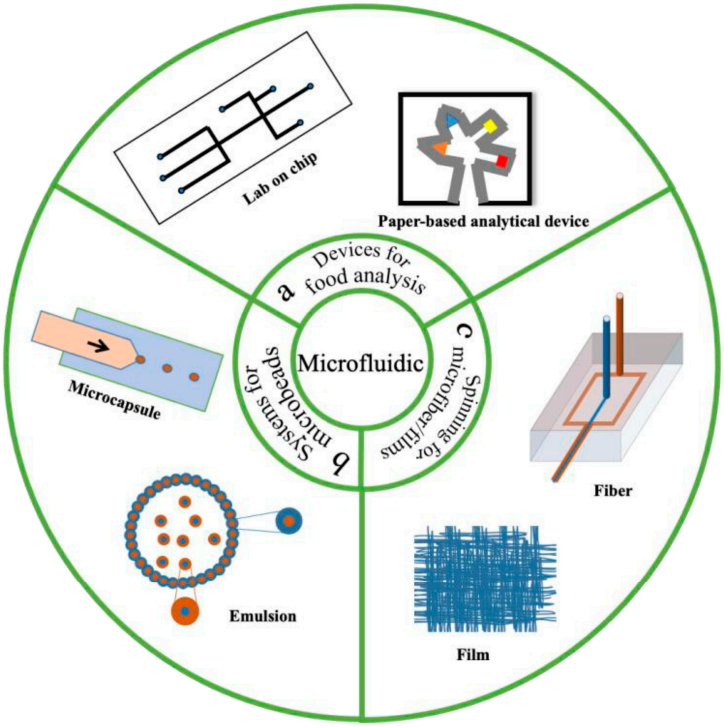


Figure 3. Potential uses of microfluidics in the field of food science as well as technology [152]. Reproduced with permission from MDPI under the terms of the Creative Commons Attribution License (Copyright, 2022).

Table 5. Evaluation of food quality and safety using microfluidic devices [151].

Target Analyte	Device Type	Key Discovery	Limitations	Regulatory Challenges	Ref.
Glutamate	Microfluidic paper-based sensor	Throughout the interval of 5×10^{-6} mol/L to 10^{-2} mol/L, a straight correlation of 0.99 was found across the hue intensities and the logarithmic of glutamate levels. The outcomes from this gadget were in line with a readily available conventional assay kit.	- Hue intensity-based detection may struggle with complex or pigmented food samples.	- Requires validation against international glutamate standards; colorimetric methods need cross-verification.	[158]
Lead and mercury ions	Aptamer-based microfluidic sensor	According to the study results, mercury ions had a detection limit of 0.70 ppb, while lead ions of 0.53 ppb. The sensor demonstrated strong sensitivity to mercury and lead when additional ions like cobalt, magnesium, calcium, and copper ions were present in competing assays.	- Potential interference from other ions in complex samples.	- Heavy metal detection limits vary globally; must comply with international guidelines.	[159]

Table 5. *Cont.*

Target Analyte	Device Type	Key Discovery	Limitations	Regulatory Challenges	Ref.
Adulterants of tadalafil and sildenafil	Hybrid microfluidic device made of polyvinyl chloride, nitrocellulose, PDMS, and elastomers	Low cut-off levels ranging from 2.0 to 9.0 ng/mL and low detection limits of 0.027–0.066 ng/mL are possible with the suggested approach. The gadget was extremely sensitive, precise, and highly accurate. The evaluation used mass spectrometry with liquid chromatography, and the outcomes were well concordant.	- Low detection limits may not suit large sample volumes; high production costs due to material diversity.	- Must meet pharmaceutical adulterant detection standards; requires reliability across food types.	[160]
Salmonella species and *Listeria monocytogenes*.	Microfluidic PDMS-PCR technology	It was noted that *Listeria monocytogenes*, along with Salmonella species, both passed the screening threshold of 10^3 and 10^4 CFU/mL. Both the selected and designated pathogens had acquisition efficiencies of more than 70%.	- Struggles with contamination below 10^3–10^4 CFU/mL; 70% acquisition efficiency may be insufficient.	- Needs to meet strict accuracy benchmarks; PCR methods require extensive validation for reproducibility.	[161]
Aflatoxin B1	A paper-based microfluidic system that uses a colorimetric test based on aptamers	The instrument demonstrated an excellent detection span from 1 pM to 1 M alongside a maximum limit of up to 10 nM. This might be employed to quickly identify contaminants in food.	- Challenges with complex food matrices or extreme environmental conditions.	- Must comply with sensitivity and repeatability requirements under standardized aflatoxin detection protocols.	[162]

4.4. Electromagnetic Technologies

Electromagnetic technology has emerged as a ground-breaking innovation in food packaging, offering diverse applications to enhance food safety, quality, and shelf life [163]. This technology leverages electromagnetic fields like radio frequencies and microwaves to manipulate and interact with food products and packaging materials. These interactions have been harnessed to achieve various objectives, such as pasteurization, sterilization, and moisture control [164]. There is a multifaceted role of electromagnetic technology in food packaging with the potential to revolutionize the way we store and preserve food.

4.4.1. Radio-Frequency Identification (RFID)

Radio-frequency identification (RFID) is a technology for automated item identification and data collection, accomplished through wireless sensors, eliminating the need for human involvement. An RFID system comprises tags and readers [165,166]. These RFID tags typically contain an identification number, which allows a reader to access corresponding information in a database and take appropriate actions [167]. When passive RFID tags

encounter radio waves emitted by the reader, the coiled antenna housed within the tag generates a magnetic field. The tag extracts power from it and transmits the data stored in the tag's memory [41]. Semi-passive RFID tags utilize a battery to uphold memory within the tag or to energize the electronics responsible for enabling the tag to modulate the electromagnetic waves emitted by the reader antenna [41]. Active RFID tags operate using an internal battery, which provides energy for running the microchip's circuitry and transmitting a signal to the reader [41].

RFID technology has proven to be highly effective in enhancing traceability and streamlining supply chain management operations due to its ability to accurately identify, classify, and monitor the movement of products throughout the supply chain. This capability allows for improved inventory management, reduced errors, and enhanced overall efficiency in logistics and distribution processes [168–170]. Research suggests that RFID technology surpasses the traditional black and white paper-based barcode system regarding food traceability [171]. It provides enhanced visibility into the supply chain, enabling rapid automation across various functions such as exception management and information sharing [165]. In the market, there are sensor-based RFID tags that, while offering valuable data collection capabilities, are typically mounted separately rather than being fully integrated into the packaging, which can limit their flexibility and adaptability in certain applications. These tags are capable of monitoring various critical parameters such as temperature, relative humidity, light exposure, pressure, and pH levels in products. By tracking these conditions, the tags can identify potential disruptions in the cold chain, which may compromise the quality and safety of food products [41]. This monitoring capability is essential for maintaining the integrity of perishable goods, ensuring that they remain safe and of high quality throughout their journey from production to consumer.

To assess the freshness of vegetables, Eom et al. [172] created an RFID-based system with O_2 and CO_2 sensors, while Martínez-Olmos et al. [173] created an RFID label that was combined using an optical oxygen indicator that included an e-system for RFID signaling plus a platinum octa ethyl porphyrin screen. Polyethylene naphthalate (PEN), a versatile polymer-based substrate that served as a covering for food packaging, had the indicator replicated on its interior [173]. Martínez-Olmos et al. [173] demonstrated that the technique, which used 3.55 mA of electrical power, was appropriate for food packing with oxygen concentrations below 2%, a detection threshold of 40 ppm, along with a resolution as low as 0.1 ppm of O_2. A novel chipless RFID sensor device has recently been created by Amin et al. [174] for wirelessly detecting food alongside other tagged goods. The designed chipless RFID sensor's unique feature is that, unlike previous RFID systems, it does not require a chip or electrical source. As a result, using it is simple and requires no maintenance [174].

4.4.2. Microwave

Microwave packaging enables the food to be heated and can endure high temperatures when microwave heating [175]. Typically, packaging materials suitable for microwaving are crafted according to the characteristics of the products and the conditions of their processing [175]. Therefore, products with varying shelf lives are packaged using distinct packaging materials [176]. In this scenario, the packaging materials employed for frozen, chilled, and shelf-stable products differ because of variations in processing and storage conditions [177]. Moreover, packaging materials can be designed in rigid and flexible forms to enhance convenience and increase efficiency. Hence, choosing materials for creating microwave packaging is crucial as each material presents distinct properties [178]. Certain functional materials, such as susceptors or self-venting substances, act similarly to intelligent materials within microwave-safe packaging [178–180]. Smart materials are

distinguished by their ability to undergo significant changes in response to controlled external stimuli, such as pH, stress, magnetic or electric fields, moisture, and temperature. These materials are integral to various devices, including actuators, sensors, and indicators, which allow them to perform functions like sensing environmental changes, responding to external conditions, and providing real-time feedback [181,182]. This adaptability makes smart materials invaluable in advanced packaging solutions, where maintaining optimal conditions and ensuring product safety are critical.

5. Advances in Materials for Intelligent Packaging

As stated by the European Union, intelligent packaging materials are materials and items that observe the state of packaged food or the surrounding environment of the food [183]. These resources can offer consumers details regarding the safety and quality of food, assisting them in making informed choices when buying and consuming. Thus, creating efficient, intelligent packaging materials necessitates contributions from diverse fields such as food science, material science, microbiology, and sensor technology [183]. Consistently observing food conditions with intelligent packaging materials can enhance food quality, minimize food wastage [184], and protect from foodborne illness. Recent advances in materials science, biotechnology, and nanotechnology have been used to construct intelligent packaging materials that can monitor, sense, and even actively interact with their contents [185]. To ensure the safety and quality of food, these components include sensors, indicators, and data recorders that can identify changes in temperature, humidity, gas composition, or microbial activity [186,187]. For example, freshness indicators give visual clues regarding the degree of spoiling of perishable commodities [188], while time–temperature indicators (TTIs) can monitor a product's thermal history [189]. Innovations in nanomaterials, such as nanocellulose [190] and other bio-based polymers, have improved intelligent packaging's sustainability by enabling the development of recyclable or biodegradable alternatives [191]. Agricultural waste can be used to make these materials, which lowers packaging's environmental impact and promotes the circular economy [192,193]. Additionally, the pursuit of sustainability and the growing demand for safer, smarter food packaging from consumers have accelerated research into bio-based sensors [194], antimicrobial films [195], and other eco-friendly alternatives. The integration of these materials with digital technologies will enable enhanced personalized and interactive consumer experiences, along with increased supply chain transparency and food security.

5.1. Bio-Based Nanomaterials

Bio-based materials originate from various biological sources, including organic waste [196], insects [197], plants [198], bacteria [198], algae [199], and fungi [200], and serve as sustainable alternatives to traditional petroleum-derived materials. The use of bio-based materials reduces dependence on fossil resources, decreases greenhouse gas emissions, and promotes a circular economy where materials can be recycled or composted at the end of their life cycle [193]. Additionally, these materials are typically biodegradable, breaking down naturally and helping to reduce plastic pollution and lessen environmental harm. In contrast, petroleum-based plastics like PET can take around 400 to 1000 years to decompose [193]. Moreover, bio-based materials typically produce fewer adverse social effects compared to petroleum-based plastics and have the potential to foster economic growth in rural communities [201,202]. For example, biodegradable materials such as cellulose nanocrystals, chitosan, and lignin are gaining attention as sustainable alternatives to petroleum-based packaging [203]. Derived from plant biomass, cellulose nanocrystals (CNCs) are strong and have good film-forming properties, which make them efficient oxygen barriers that can extend food shelf life by lowering oxidation [203]. Similarly to this,

chitosan, a biopolymer made from chitin, has antibacterial qualities and creates flexible, biodegradable films that are appropriate for use in active food packaging [204]. Lignin, a widely available by-product from the pulp and paper industry, offers antioxidant and UV-blocking capabilities, which improve the functionality of bio-based packaging films [205]. When integrated into biopolymer systems, these materials enhance the mechanical strength, barrier efficiency, and functional performance of packaging films, contributing to a reduced environmental footprint. Additionally, incorporating these natural polymers into smart and active packaging offers a sustainable solution to minimize dependence on single-use plastics while advancing circular bio-economy practices in the packaging industry.

5.2. Edible Films and Coatings

Utilizing edible films is one of the most straightforward and cost-effective methods for creating smart food packaging, including blend and coating films [183]. Blended films are developed by integrating a sensor with a film-forming substance, typically synthetic or natural polymers [183]. The sensor in these films must exhibit strong compatibility with the polymer matrix to ensure uniformity and effectiveness. There are three primary techniques used to fabricate blended films: solution extrusion, casting, and thermo-compression [183]. Among these, the solution casting method is the most widely employed in the literature. This preference is due to its cost-effectiveness, simplicity, and rapid execution in a laboratory setting, making it an accessible and efficient choice for researchers and manufacturers alike [183]. For instance, Musso et al. [206] developed pH-sensitive smart food packaging materials by incorporating anthocyanins, which act as sensors, into gelatin solutions for film formation. The process involved casting the anthocyanin–gelatin mixture onto a plate and then drying it to form the film. Similarly, Pereira et al. [207] created humidity-monitoring food packaging materials by combining zinc oxide nanoparticles as sensors with glycerin as a plasticizer into a gelatin solution, followed by casting and drying. Similarly, Tshamisane et al. [208] formulated pH-sensitive edible films by integrating betalain as a sensor into a mucilage-based matrix, utilizing cellulose nanofiber as a plasticizer through the solvent casting technique. While this solvent casting method is widely used due to its simplicity and cost-effectiveness, it is generally not well suited for the large-scale commercial production of films [183]. As a result, the thermo-compression technique has become more favorable for large-scale production due to its efficiency and speed in film preparation [209]. This method creates composite films by blending the sensor, film-forming polymers, and other additives. The mixture is then compressed using a hot press for a brief period to form the film [209]. For example, the hot-pressing technique has been used to produce pH-indicating blend films by incorporating anthocyanins into a fish gelatin matrix [209] and integrating blueberry residues into a tapioca starch matrix [210]. This process typically involves the use of an extruder, along with controlled temperature, pressure, and screw speed settings.

Similarly, Zhai et al. [211] employed the extrusion technique to create ammonia-monitoring packaging materials by integrating curcumin as the sensor into a low-density polyethylene matrix. Another prevalent approach currently employed in smart packaging is coating films. In this technique, the indicator is positioned on the film's surface rather than distributed throughout the film [183]. Coating films are typically produced by blending the sensor with an appropriate dispersion medium, which is then applied to a polymer film through coating or printing [183]. For instance, Sukhavattanakul and Manuspiya [212] developed a hybrid nanocomposite coating composed of bacterial cellulose nanocrystals–silver nanoparticles/alginate–molybdenum trioxide nanoparticles (BCNCs–AgNPs/alginate–MoO_3NPs). This composite was applied onto a PET substrate using thermal spraying technology, resulting in transparent coatings with thicknesses ranging

from 0.73 to 2.18 µm. These coatings were effective in tracking the freshness of minced pork by detecting hydrogen sulfide (H_2S) gas, a spoilage indicator [183]. However, there is a growing trend towards the use of biopolymer packaging with natural sensors, driven by environmental concerns associated with synthetic polymers. Synthetic polymers are slow to degrade and may release chemicals that can compromise food quality [213]. Naturally occurring biopolymers such as polysaccharides, proteins, and lipids are increasingly used as the primary components for creating biodegradable packaging, including coatings [214]. Current research focuses on integrating naturally sourced pigments from plant materials and food by-products into coatings [215]. These natural resources are abundant, safe, cost-effective, and environmentally friendly. They offer a responsive, reliable, and non-invasive means of monitoring food quality [216]. This shift towards biopolymer-based coatings with natural sensors represents a significant advancement in the development of sustainable, intelligent packaging solutions that align with environmental and health-conscious consumer demands.

Plant Wastes as Viable Alternative Materials for Food Packaging

Discarded food or edible waste, such as peels, oil cakes, husks, barks, pulp, seeds, and bagasse, constitute approximately 30–50% of the overall weight of food [217], making them easily accessible. The assessment of the usefulness of food waste depends on analysing its composition and considering the expenses involved in extracting valuable compounds. These food wastes may contain bioactive elements like tannins, polyphenols, and flavonols, which could enhance the antimicrobial and antioxidant capabilities of the packaging system [218,219]. Natural substances, such as brazilin, anthocyanins, curcumin, betalains, tannins, chlorophyll, and other phenolic compounds, have proven valuable in food preservation. These compounds can be extracted from food waste, enhancing environmental sustainability while providing valuable resources for the food packaging industry. The packaging industry gains access to cost-effective options for value addition or valorization by repurposing these waste-derived compounds. Therefore, these edible films can be promoted as packaging materials that are environmentally friendly and sustainable, aligning with the growing demand for green packaging solutions. The bran derived from black rice milling is particularly rich in polyphenolic anthocyanins, making it a promising candidate for incorporation into functional foods [220].

Smart films, composed of gelatin and infused with anthocyanins from black rice bran, have demonstrated efficacy as freshness indicators for pork and seafood, as evidenced in studies conducted in the literature [221–223]. Following the production of blueberry juice, a substantial amount of leftover pomace containing valuable phenolic compounds, including antioxidants and anthocyanins, is generated [224]. Films produced from blueberry agro-waste and comprising corn/cassava starch have shown notable pH sensitivity. These films hold promises for monitoring food freshness [210,225,226]. Kurek et al. [227] examined the utilization of blackberry pomace and blueberry residue in a chitosan matrix. They enriched corn starch with anthocyanins extracted from black bean seed coat extracts and integrated black soybean seed coat extracts into the chitosan matrix, as highlighted by Ganesan and Xu [228]. The potential use of edible films in packaging perishable high-protein foods is significant, particularly given their sensitivity to pH [229,230]. Grape skin, abundant in cellulose, pectin, anthocyanins, and various polyphenolic compounds, offers valuable components. Ma and Wang [231] employed anthocyanins extracted from grape skin in a cellulose matrix to monitor milk spoilage. Furthermore, Chi et al. [232] incorporated grape skin extract with anthocyanins into a κ-carrageenan film to monitor pork freshness [232]. Betalain extracts from red pitaya peels were integrated into starch/polyvinyl alcohol (PVA) and glucomannan films and subsequently used to assess the quality of shrimp and

fish, respectively [233,234]. Many studies have investigated the utilization of bioactive polyphenolic pigments derived from discarded food, incorporating them into biopolymeric films, as detailed in Table 6.

Table 6. Bioactive compounds from discarded food waste with biological activity, their origins, and techniques for extraction.

Biologically Active Substances	Sources	Extraction Method	Ref.
Anthocyanin	Sweet potato/potato	PSP (50 g) was mixed in a 40% ethanol solution (500 mL) and stirred at (60 °C for 6 h). The resulting mixture was then filtered and concentrated at (50 °C). The extract was subjected to freeze drying under vacuum.	[235]
	Red radish	Radish underwent cleaning, cutting, and vacuum drying at 65 °C. Ground and incorporated into an 80% ethanol solution, the mixture was stirred at 35 °C for 6 h. After filtration, the supernatant was concentrated at 45 °C in the dark. The extract was freeze-dried, nitrogen-sealed, and stored in dark bottles at 4 °C.	[236]
	Mulberry	Ground mulberry (100 g) was extracted using an 80% ethanol and 1% HCl solution at 4 °C for 24 h. Centrifuged at 10,000× *g* for 30 min, concentrated the supernatant at 50 °C, and vacuum-dried.	[237]
	Red cabbage	The red cabbage was crushed and blended with 85% ethanol. The pH was then adjusted to 2 using 1 M of HCl, and the mixture was kept in darkness for 24 h at 4 °C. Centrifuged at 4000 rpm, filtered and neutralized the solution to a pH of 7 using 2M of NaOH. Concentrated the mixture at 40 °C, and then freeze-dried it at 4 °C.	[238]
	Purple potato	Blended 25 g of PSP powder with a 500 mL solution of ethanol acidified. Utilized ultrasound assistance for extraction under the conditions of 270 watts, 50 degrees Celsius, and 30 min, filtered and evaporated (45 °C). The extract was subjected to freeze drying under vacuum conditions.	[237]
Betalains	Cactus pears	Fruits were juiced and soaked in a 2 L, 60% ethanol solution at 4 °C for 12 h. Centrifuged at 10,000× *g* for 30 min, then concentrated. The extract underwent purification and vacuum drying.	[239]
	Dragon fruit peel	Minced peels (300 g) underwent double extraction using 30% ethanol solution (800 mL each time) at 4 °C overnight. The extract was undergoing filtration and centrifugation at 8000× *g* for 15 min at 4 °C. The sample underwent purification, concentration, and vacuum drying.	[240]

Table 6. *Cont.*

Biologically Active Substances	Sources	Extraction Method	Ref.
	Amaranthus leaf	The leaves were isolated, cleansed, and dehydrated in a 45 °C hot air oven. The powder was mixed with distilled water and 0.1M of citric acid (1:10 ratio) and stirred at 150 rpm for 18 h. Centrifuged at 12,100× *g* for 30 min. The supernatant was filtered to yield the extract.	[241]
Chlorophyll	Spinach	Spinach underwent a 15 min blanching process and was then high-speed crushed for 4 min. A solution in water was kept in a plasma freezer at −30 °C.	[242]
	Green tea and pu-erh tea	Combined 2 g of tea powder with 200 mL of distilled water, subjected to controlled conditions (90 °C, 20 min), and then filtered.	[243]
Chlorophyll and Carotenoids	Green tea and basil	Basil leaves were steeped in 100 mL of distilled water and heated at 100 °C for 40 min. The samples were cooled, filtered, and then preserved in opaque containers.	[244]
Tannins	Cashew nut testa	Testa underwent milling at 500 rpm for 1 h, followed by the addition of MilliQ water at a 1:10 ratio. The blend was mixed and placed in a water bath at 37 °C for one hour. Centrifuged at 10,000× *g* for 10 min at 4 °C. Filtered supernatant underwent freeze drying.	[245]
	Pomegranate peel	Pomegranates (500 g) were cleaned, and their peel and flesh were separated. The skin and pulp were separately ground and extracted at 4 °C for 24 h using a 1% HCl ethanol solution. The samples underwent centrifugation at 8000× *g* for 20 min, followed by evaporation at 50 °C and vacuum drying.	[246]
Curcumin	Turmeric residue	Turmeric residue was acquired using the Soxhlet method at 47 °C for 3 h. An ethanol/isopropanol blend served as the solvent. The leftover material underwent soaking, grinding, sifting, and drying.The liquid portion was centrifuged and then dried to yield turmeric flour.	[247]

5.3. Smart Polymers

Smart polymers, also known as stimuli-responsive or intelligent polymers, are materials that can undergo reversible changes in their properties in response to external stimuli [248]. These modifications occur in reaction to shifts in the physical or chemical conditions of the surroundings, including changes in temperature, pressure, electric or magnetic fields, ionic strength, or pH [249–251]. Research on the creation and practical use of polymers responsive to stimuli has experienced substantial growth in recent decades. The ability of smart polymers to respond to specific environmental conditions makes them versatile and applicable in various fields, including medicine [252], biotechnology [253,254], drug delivery [255–257], textiles [258], and sensors [259]. For instance, temperature-responsive polymers can be incorporated into labels or packaging materials to indicate temperature exposure [260]. These can be applied as coatings, inks, or labels

that change color or texture in response to temperature variations. Prominent examples of smart polymers include temperature-responsive polymers and pH-sensitive polymers.

5.3.1. Temperature-Responsive Polymers for Temperature Indicators

Elevated temperatures can accelerate microbial growth, thereby increasing the risk of food spoilage [261]. Additionally, higher temperatures promote the production of ethylene in climacteric fruits and vegetables, which hastens ripening [262]. Ethylene inhibitors, such as 1-methylcyclopropene (1-MCP), are effective in slowing this process [263]. Poly(*N*-isopropylacrylamide) (PNIPAAm) is a thermoresponsive polymer with a lower critical solution temperature (LCST) of 32 °C [261]. The LCST can be adjusted by copolymerizing PNIPAAm with hydrophobic or hydrophilic monomers, tailoring its temperature sensitivity [261].

For instance, Ju et al. [264] synthesized a thermosensitive amphiphilic polymer, poly(N-isopropylacrylamide-co-N,N-dimethylacrylamide)-b-poly(D,L-lactide) (PN-co-DM-bPA), to create temperature-responsive release materials. This polymer was used to encapsulate the hydrophobic antimicrobial compound curcumin (Cur), forming curcumin-loaded micelles (CurMs). Electrospinning was then applied to embed CurMs into a polyvinyl alcohol (PVA) nanofiber film [264]. These micelles remained stable in aqueous solutions below the LCST, but, as the temperature rose above 42 °C, the PNIPAAm segment shifted from hydrophilic to hydrophobic, disrupting micelle stability and enhancing curcumin release. After 96 h, cumulative release rates of curcumin from the nanofiber film reached 32.15%, 33.36%, and 63.47% at 25 °C, 37 °C, and 42 °C, respectively, demonstrating the film's ability to modulate curcumin release in response to temperature fluctuations [264]. This thermoresponsive behavior highlights the potential for developing intelligent antimicrobial materials.

Similarly, Xia et al. [265] developed a nanofiber film composed of polylactic acid (PLA) infused with lemon essential oil through electrospinning. The application of a thermosensitive film, coated with PNIPAAm, successfully preserved the nutritional quality and appearance of blackberries, as shown in Figure 4A [265]. In another study, Douaki et al. [266] fabricated a nanofiber mat containing cinnamon essential oil (CEO) using poly(propylene carbonate) (PPC). The mat was coated with poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) on one side and PNIPAAm on the other [266]. The PEDOT:PSS layer provided conductivity, enabling the mat to generate heat when voltage was applied. Meanwhile, the PNIPAAm layer restricted CEO release under ambient conditions, with minimal release observed at 20 °C (below the LCST). When a 2 V voltage was applied, the temperature exceeded the LCST, causing PNIPAAm to undergo reversible volume and shape changes. At 40 °C (above the LCST), the total CEO release exceeded 60%, achieving a 95% free radical scavenging capability. This system can be integrated with a freshness sensor to detect volatile organic compounds from spoiled food, converting the signal into an electrical stimulus that triggers bio-compound release, as illustrated in Figure 4B [266]. In addition to thermosensitive materials, pH-sensitive polymers are gaining attention for their potential in spoilage detection. These polymers can respond to changes in pH caused by food degradation, offering a visual or electrical indication of spoilage, thereby enhancing food safety and quality monitoring systems.

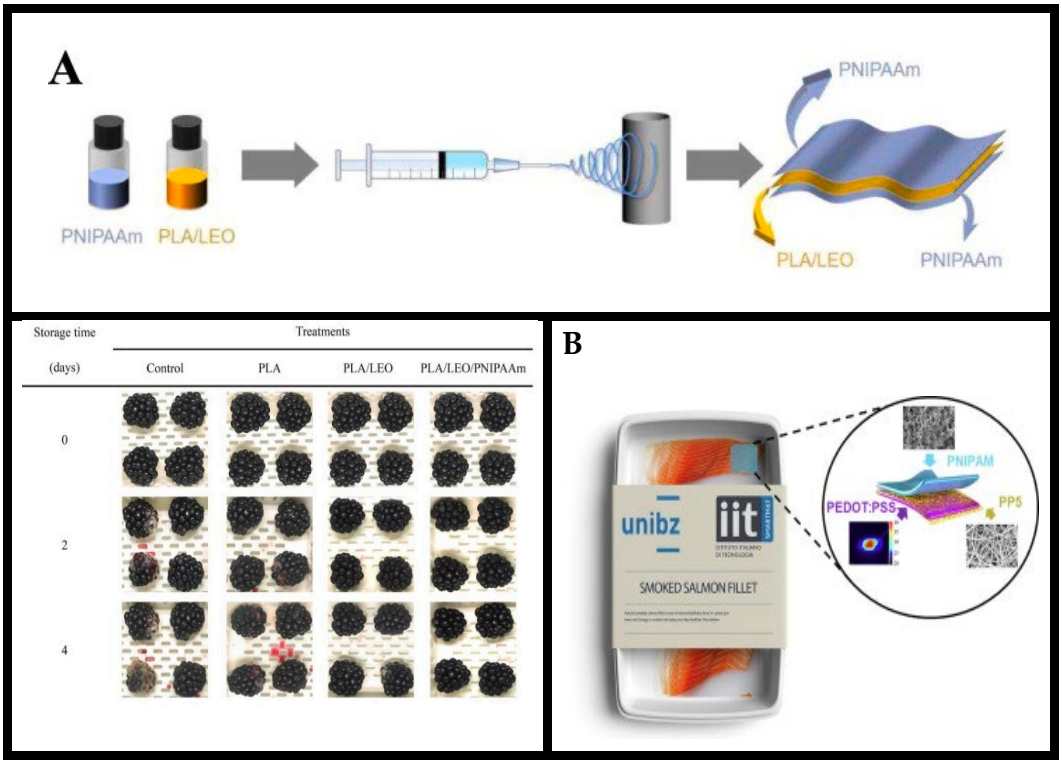


Figure 4. Temperature-responsive polymers of (**A**) lemon essential oil [265] and (**B**) cinnamon essential oil based on PNIPAm [266]. Both figures are reproduced with permission from Elsevier (Copyright, 2024).

5.3.2. pH-Sensitive Polymers for Spoilage Detection

Colorimetric indicators sensitive to pH changes have gained significant attention as tools for monitoring food freshness due to the direct relationship between pH fluctuations and food spoilage (Figure 5) [267]. These indicators work by changing color in response to the pH variations caused by microbial activity or chemical reactions during food deterioration [216,268,269].

Typically, a pH-responsive indicator consists of a dye that undergoes a visible color shift when exposed to different pH levels in food samples [270]. To ensure stability, the dye is immobilized within a supporting matrix that facilitates its application on packaging materials [270]. Such indicators are designed to detect undesirable metabolites produced during spoilage, including acids, amines, and sulfur compounds, by exhibiting distinct color changes that signal the extent of degradation [271]. These changes are primarily driven by the breakdown of sugars, proteins, and fats through enzymatic and microbial processes, which are further influenced by the composition of the food and its storage conditions [26].

Microorganisms release various metabolites, including water, hydrogen sulfide, carbon dioxide, and amines, which alter the food's acidity or alkalinity [272]. Freshness indicators use pH-responsive dyes to detect these changes and transform them into visible signals recognizable by consumers [273]. The observed color changes are often due to protonation or deprotonation reactions involving carboxylic acid or amidocyanogen groups [272]. Moreover, previous research has suggested that dissociation is likely to occur within a range of 20% to 80% when only one dissociable group is present, and the pH varies by two units [274]. Recent studies have focused on anthocyanin (ACN)-based dyes derived from natural sources, such as red cabbage, purple eggplant, purple corn, black carrot, and purple sweet potato [233,275–278]. These dyes are combined with non-toxic polymeric matrices

like cellulose nanofibers, gelatin, starch–cellulose nanocomplexes, and alcohol, ensuring safety and stability in food packaging applications [275,279–281]. pH-sensitive indicators are now used to assess the spoilage of perishable items, including dairy, fish, meat, fresh fruits, and vegetables, by detecting microbial activity through color changes in indicator films [267].

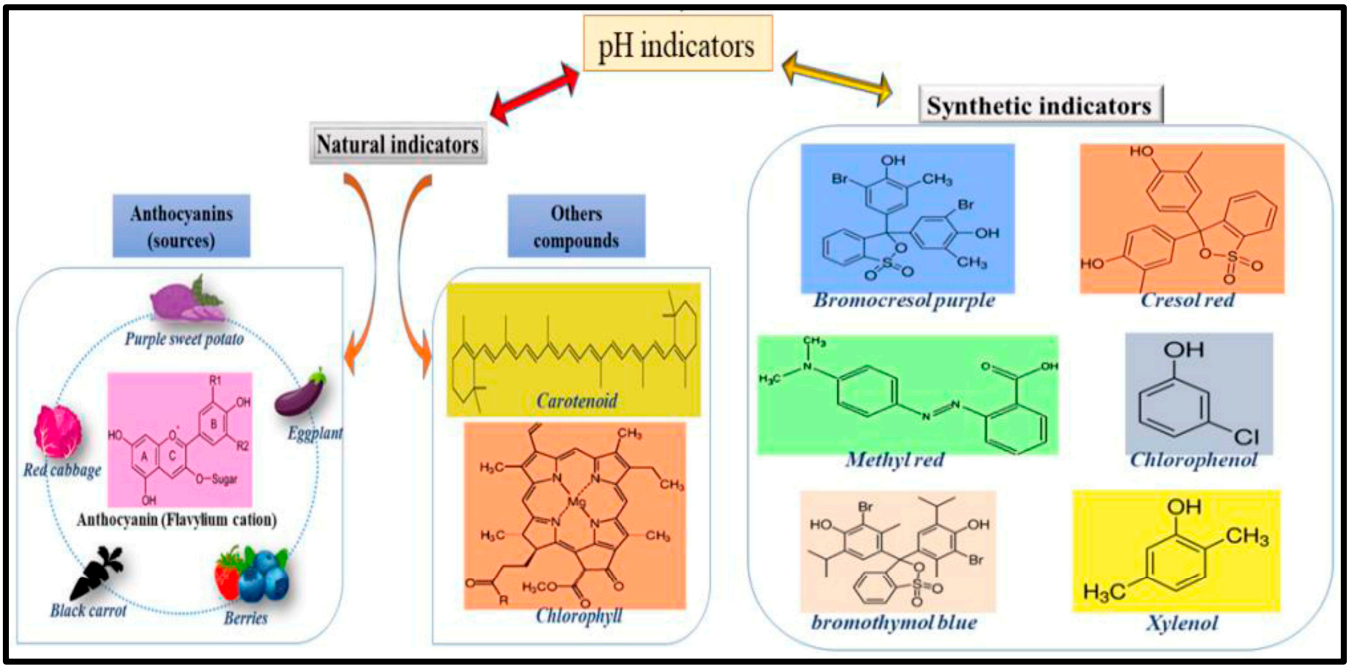


Figure 5. Various types of pH indicators employed in intelligent packaging [267]. Reproduced with permission from Taylor and Francis (Copyright, 2024).

Dairy products, especially milk, are highly susceptible to microbial spoilage due to their high nitrogenous compound content, such as amino acids and proteins [282]. Lactic acid bacteria in milk produce lactic acid, accelerating spoilage [27]. As a result, different indicators that change color depending on the pH have been created to monitor the condition and spoilage of dairy products. For example, Ebrahimi Tirtashi et al. [283] developed a pH-responsive film using cellulose, chitosan, and carrot anthocyanins to monitor milk freshness. The film was effective in a pH range of 2 to 11. Within two days of regular storage, a change in the color of the dye was observed, shifting from blue to violet rose, indicating that the stored milk had spoiled [283]. Similarly, meat and fish spoilage results from a microbial and enzymatic breakdown [284–286], producing volatile nitrogenous compounds like phenylethylamine, histamine, creatinine, and sulfur-containing compounds such as hydrogen sulfide [287–289]. These compounds cause pH fluctuations, making pH-responsive colorimetric indicators valuable tools for assessing food quality and safety in smart packaging systems

Zhai et al. [211] developed a bionanocomposite of gellan gum and silver nanoparticles to create a color-based sensor for detecting H_2S. This sensor was used to monitor the freshness of chicken breast and silver carp. Initially, the indicator film appeared yellow during storage, but it turned colorless once H_2S was produced from the spoiled meat and fish samples [192,193]. In a similar vein, [290] designed dual-sensor tags using two pH indicators, methyl red (MR) and bromocresol purple (BCP), to evaluate the storage environment of packaged beef. As the storage time increased, the fats or proteins in the beef underwent degradation, resulting in the generation of nitrogenous volatile compounds [290]. Consequently, these compounds caused the MR indicators to change from red to yellow and the BCP indicators from yellow to purple. By observing significant color changes,

one can directly detect the deterioration of packaged meat and fish. Therefore, colorimetric indicators sensitive to pH show great potential for incorporation into food-quality monitoring systems.

6. Applications of Intelligent Packaging for the Maintenance of Food Quality

Developing efficient measures for assessing the quality of food has remained crucial for sustainability and the prevention of wastage of food items, especially perishable fruits and vegetables. The application of intelligent packaging thus provides an immediate quality assessment of these perishable products [269]. Numerous research investigations have been conducted to assess the freshness of various products such as fresh produce, seafood, meat, and others. Examples of parameters being assessed include the emission of organic acids in many fruits, vegetables, and milk [291] and the generation of nitrogenous substances in seafood and meat, which leads to a rise in pH level [279]. Additionally, the substances generated by deteriorating microorganisms have a detrimental impact on the taste, nutritional content, and aroma [231]. Therefore, this section will assess various real-life applications of intelligent packaging under the following subsections.

6.1. Fresh Produce

Fresh produce such as fruits and vegetables are crucial for a healthy diet because they contain vital nutrients like vitamins, minerals, and fiber [292]. However, it is crucial to package them properly to maintain their freshness and safety, as they are easily prone to damage, spoilage, or contamination. Intelligent packaging thus plays an important role in ensuring that our fresh produce is safe to consume, high-quality, and visually appealing on display in stores. Therefore, effective packaging not only safeguards against physical damage and contamination but also extends the shelf life, eases handling, and ensures that customers are adequately informed about the condition of the product being consumed [293]. Hence, as consumer preferences change and environmental awareness increases, there is a constant quest for innovative packaging methods that enhance the preservation of fresh produce [294].

The quality of fresh produce after it has been harvested can be influenced by numerous factors, including physical damage, distribution, and effective storage management, which is the primary determinant in delivering a high-quality product with an extended shelf life to the customer [295]. Storage management needs to consider factors such as the product's respiration rate, ethylene production and buildup, and its sensitivity to various important variables like storage temperature and initial gas levels. Additionally, maintaining high relative humidity is crucial for extending the freshness and shelf life of perishable produce [296]. To address this, numerous studies have explored the use of potassium permanganate (KMnO4) as an ethylene scavenger to assess its physical and chemical effects on fresh produce [297]. Research on KMnO4's impact has largely centered on climacteric fruits, such as apples, bananas, and mangoes, due to their significant ethylene production and sensitivity. For instance, Álvarez-Hernández et al. [297] demonstrated the efficacy of KMnO4 in mitigating ethylene-related ripening in mangoes. Table 7 summarizes key studies investigating the application of ethylene scavengers in packaging systems for preserving fresh produce.

Table 7. Overview of ethylene scavenger applications in packaging solutions for extending the shelf life of fresh produce [295]. Reproduced with permission from Springer, copyright (2024).

Ethylene Scavengers	Application Form	Type of Fresh Produce	Advantages	Ref.
TiO_2	Chitosan film	Tomato	Slowed down the maturation of tomatoes stored at 25 °C and 50% relative humidity, resulting in alterations in their quality.	[298]
Silica gel	Not specified	Pointed gourd	Minimized spoilage and lowered the disease index by extending the preservation period for up to 8 days with reduced chlorophyll content loss when stored at temperatures between 29.4 and 33.2 °C and a relative humidity of 68–73%.	[299]
Zeolite (clenoptelolite)	Filter	Peach	Decreased firmness and weight loss were observed, along with a delayed rise in pH. The overall appearance remained in good condition, and a minor impact on both SSC (soluble solid content) and TA (total acidity) was noted when stored at a temperature of 0 °C for a duration of 36 days.	[300]
Potassium permanganate	Not specified	Guava	The guava's shelf life, when kept at 4 °C with 85% relative humidity, was prolonged to 32 days. During this time, it maintained a significant level of phenol and ascorbic acid content without experiencing any negative effects from growth.	[301]
Vermiculite	Sachet	Sapodilla	A slower reduction in pulp firmness and vitamin C breakdown was observed when stored at 25 °C (with 54% relative humidity) for a duration of 5 days.	[302]
Zeolite	Filter	Iceberg, lettuce	Reduced the loss of firmness in texture and minimized alterations in color. Delayed the decrease in weight, pH levels, and the browning of tissues over a period of 21 days.	[303]
Vermiculite	Sachet	Baby banana	There was a delay in the yellowing of the peel, a slower increase in soluble solid content (SSC), a decrease in titratable acidity (TA), the reduced loss of firmness and weight, and a minimized increase in the SSC/TA ratio during storage at 18 °C for 16 days at a relative humidity of 70–80%.	[304]
Nano-ZnO	A polyvinylchloride film that has been treated with nano-sized zinc oxide	Fresh-cut apple	The decrease in fruit decay, a decrease in ethylene production, the preservation of °Brix and titratable acidity, and the suppression of enzyme activity.	[305]

Table 7. *Cont.*

Ethylene Scavengers	Application Form	Type of Fresh Produce	Advantages	Ref.
Halloysite nanotube	Low-density polyethylene film	Tomato, strawberry, and banana	The extended durability of bananas and tomatoes enclosed in films and stored at a temperature of 4 °C.	[306]
Zeolite infused with $KMnO_4$	high-density polyethylene HDPE films	Kiwifruit	Increased firmness and elevated vitamin C levels, with no specified shelf life.	[307]
Silver nanoparticles, titanium dioxide nanoparticles, and kaolin nanoparticles.	polyethylene film	Strawberry	Enhancements in quality were observed, with physiological, sensory, and physicochemical attributes showing improvements. Specifically, nano-packaging led to reduced malondialdehyde and anthocyanin content, while normal packing maintained these parameters at their original levels.	[308]
Kaolin, nano-Ag and nano-TiO_2	polyethylene film	Chinese jujube	The use of nano-packaging results in several advantages, including improvements in the physical and sensory characteristics of the fruit, the prevention of fruit softening, reduced weight loss, the prevention of browning, and the control of climatic changes. Additionally, it effectively manages ethylene levels, maintaining a maximum ethylene content of 17.6 μL/kg h for the control group on the third day and 9.2 μL/kg h for the nano-packaging group on the sixth day of storage.	[305]
Alumino-silicate and zeolite-based materials	Low-density polyethylene films	Small pieces of broccoli	Improvement of overall quality and increase in shelf life up to 20 d at 4 °C.	[309]

6.2. Seafood

Microbial spoilage is the primary factor contributing to the degradation of seafood, leading to undesirable flavors and unpleasant tastes. Total volatile basic nitrogen (TVB-N) such as ammonia, diethylamine, and trimethylamine contribute to the enzymatic and microbial breakdown of protein-rich foods, resulting in pH fluctuations within packaged food items [282]. These fluctuations can be observed by using a pH-indicating smart film designed to evaluate the degradation of the product [279]. Fish, one of the most sought-after seafood, is extremely prone to spoilage because of its elevated protein and water content [282]. It is prone to enzymatic and microbial decay, diminishing its nutritional value and increasing the risk of contracting various foodborne illnesses [282]. Therefore, the assessment of fish spoilage often relies on detecting the presence of TVB-N, which serves as a key indicator of freshness [282]. The pH rise, induced by the enzymatic degradation of trimethylamine oxide by microorganisms, leads to an elevation in the concentration of TVB-N [235]. In this vein, several research efforts have aimed to create real-time indicators for identifying the spoilage of fish (Table 8). For instance, blended films exhibited a color

change when the fish products spoiled, serving as a visual monitoring film for detecting fish spoilage.

Table 8. Characteristics and applications of bioactive compounds in seafood and meat preservation.

Application	Mode of Action	Type of Packaging Material	Properties Evaluated	Ref.
Fish	pH (TVB-N)	Carboxymethyl cellulose/starch	Light barrier, film thickness, and TS	[235]
Pork	pH (TVB-N)	Agar/potato starch	-	[310]
Shrimp	pH (TVB-N)	Starch/PVA	Thermal stability, film thickness, and light barrier	[311]
Fish	pH (TVB-N)	Chitosan/corn Starch	Light barrier and thermal stability	[268]
Pork	pH (TVB-N)	Chitosan/PVA	Mechanical properties (EAB and TS)	[312]
Poultry	CO_2	Ethyl cellulose	Maintained in a cold storage environment for several weeks	[86]
Fish	pH (TVB-N)	Starch/PVA	EAB and film thickness	[313]
Pork	pH (TVB-N)	Chitosan/starch/PVA	Antioxidant and TS	[314]
Shrimp	pH (TVB-N)	Chitosan	Film thickness	[315]
Chicken	pH (TVB-N)	Agarose solution		[316]
Pork	pH (TVB-N)	k-carrageenan	Film thickness, light barrier, hydrophobic	[232]
Fish	Time Temperature	Cellulose-based	-	[317]
Shrimp	pH (TVB-N)	Cellulose		[318]
Seafood	pH (TVB-N)	Chitosan/chitin	Antioxidant and UV barrier	[223]
Shrimp and Hairtail	pH (TVB-N)	Gelatin/oxidized	Antioxidant, water and oxygen barrier, UV barrier	[222]
Fish	pH (TVB-N)	Tara gum	Water and oxygen barrier	[319]
Shrimp	pH (TVB-N)	Fish gelatin	UV–vis barrier, mechanical properties (EAB and TS), water vapor barrier, antioxidant	[320]
Shrimp	pH (TVB-N)	Cellulose-based paper	-	[321]
Lard (Pork)	pH (TVB-N)	k-carrageenan	Antioxidant, light Barrier, oxygen Barrier, mechanical Properties (EAB and TS), thermal stability	[322]
Pork	pH (TVB-N)	Chitosan	Antioxidant, film thickness, light barrier, EAB	[323]
Pork	pH (TVB-N)	Starch	Thermal stability, antioxidant, water barrier, film thickness, UV–vis light, TS	[233]

Table 8. *Cont.*

Application	Mode of Action	Type of Packaging Material	Properties Evaluated	Ref.
Pork	pH (TVB-N)	Cassava starch	Antioxidant, water barrier, UV–vis light, film thickness, TS	[324]
Chicken	pH (TVB-N)	Sago powder	Film thickness, low water solubility	[87]
Fish/Chicken	pH (TVB-N)	Gelatin/PVA	Film thickness, antibacterial, oxygen, and water barrier, antioxidant, TS	[241]
Fish	pH (TVB–N)	Glucomannan/ PVA	-	[234]
Shrimp	pH (TVB-N)	Starch/PVA	Water barrier, film thickness, antimicrobial, mechanical properties (EAB and TS), antioxidant	[240]
Shrimp	pH (TVB-N)	Chitosan/PVA	Water barrier, film thickness, mechanical properties (EAB and TS), antimicrobial, UV–vis light barrier, antioxidant	[239]
Pork and shrimp	pH (TVB-N)	k-carrageenan	Light barrier, TS, moisture and oxygen barrier	[325]
Shrimp/meat	pH (TVB-N)	Chitin	Light barrier, TS, antioxidant, water barrier	[223]
Shrimp	pH (TVB-N)	Pectin powder/ Glycerol	Antioxidant, water barrier, film thickness, antimicrobial, thermal stability	[326]
Shrimp	pH (TVB-N)	Tara gum/PVA	Thermal stability, EAB, water barrier	[319]

Another practical example is shrimp, where edibility is closely linked to its freshness. The assessment of shrimp quality typically involves evaluating microbial levels, employing sensory analysis techniques, and measuring the total viable count (TVC) and total volatile basic nitrogen (TVB-N) levels. These parameters are critical indicators of shrimp freshness and overall quality [327]. Sensory evaluation is the most straightforward method, but its effectiveness is limited when dealing with packaged products. Additionally, the assessment of TVB-N levels is time consuming and necessitates access to laboratory facilities [216]. Therefore, developing a straightforward and feasible approach for assessing shrimp quality that can be seamlessly integrated into the packaging process is essential. Diverse studies have already documented colorimetric indicators using natural pigments to assess the quality of shrimp (refer to Table 8). All these ingestible films exhibited responsiveness to the volatile substances produced during shrimp spoilage, resulting in noticeable alterations in color.

6.3. Meat

Meat and meat products primarily undergo spoilage because of enzymatic and microbial breakdown, which generates different volatile amines through the degradation of proteins [328]. These modifications lead to fluctuations in the pH of the packaged food substance [322]. The proteins found in meat are susceptible to the growth of mold and bacteria [329]. The degradation process has the potential to liberate a significant quantity of TVB-N, such as amines and ammonia, leading to a change in the pH of pork packaging [325]. Fresh pork is highly prone to microbial contamination and enzymatic degradation when it encounters the air [330]. Various bioactive compounds embedded inside some smart film materials have thus been employed as indicators of quality in meat products (Table 8). These ingestible films demonstrated the efficient detection of pork spoilage by displaying their indicator capabilities through a noticeable visual change in color. Poultry meat contains high levels of water and protein, creating an ideal environment for the proliferation of microorganisms, significantly increasing the perishability of these food items [331]. The detection of spoilage in chickens can be effectively facilitated by using anthocyanins extracted from Jamun fruit skin [316] and by applying Amaranthus leaf extract [241]. These natural indicators provide a practical means for monitoring freshness and ensuring food safety.

7. Challenges of Intelligent Packaging in Food Packaging

Intelligent packaging has brought significant advancements to the packaging, distribution, and consumption of food products. It offers several key benefits, such as the ability to monitor critical factors like temperature, humidity, and freshness, ensuring that consumers receive products in optimal condition [332]. Additionally, the enhancement of consumer experience through interactive features like QR codes, augmented reality, and NFC tags provides valuable information and engagement opportunities, which are increasingly popular in the food industry [39,194,333]. However, despite these advantages, several challenges hinder the widespread adoption of intelligent packaging. One of the primary challenges is the availability and cost of indicators and sensors. The high cost is often due to the expensive development and production processes [334]. In fact, packaging costs can account for 50% to 100% of the total expenses for the final product, which is far above the recommended threshold of 10% of the product's value [335]. Moreover, the requirement for advanced instrumentation restricts the implementation of certain innovative solutions. Furthermore, there are technological scalability issues when incorporating smart components like colorimetric sensors, RFID tags, or data trackers into biodegradable films, particularly when moving from laboratory to industrial manufacturing [95]. In addition, consumer satisfaction and perception is another challenge. The use of indicators and sensors can influence purchasing behavior, as consumers are more likely to return products with discolored freshness indicators, even if the product is still safe for consumption. Frequent encounters with color variations in product labels could erode consumer trust in the brand, potentially leading to increased levels of unsold merchandise [335]. This suggests that, while intelligent packaging offers valuable information, it may inadvertently impact consumer confidence and purchasing decisions. Furthermore, relying solely on intelligent packaging does not guarantee the best product quality, as there is a risk of system misuse or failure [336]. Product quality can deteriorate due to various factors, and assessing a single parameter is often insufficient to comprehensively evaluate a product's overall quality [28]. External conditions such as light, temperature fluctuations, and mechanical stress can also limit the effectiveness of intelligent packaging, leading to products being incorrectly labeled as unsuitable for consumption, even when they are perfectly safe [28]. Conversely, these

technologies may fail to detect the deterioration of a product, posing potential risks to consumer health [337].

Since the technologies and materials used in intelligent packaging must adhere to environmental and food safety regulations in many jurisdictions, regulatory barriers also affect its uptake [95]. Strict safety regulations must be followed by packaging materials that come into close touch with food to prevent damaging elements from escaping or changing the composition of the food [293]. Regulations on the use of additives, migration limitations, and material safety are enforced by authorities like the FDA (U.S.), EFSA (Europe), and other regional agencies [338]. Intelligent packaging, which frequently includes sensors (like colorimetric indications) or active ingredients (like antimicrobial agents), adds another level of complexity because these functional components need to be assessed for both safety and efficacy [24]. The compositional heterogeneity, potential allergenicity, and biodegradability claims of bio-based products, such as natural pigments or biodegradable polymers, may present extra regulatory hurdles [293]. Compliance is made more difficult by the absence of standardized international standards, which force producers to deal with various regulatory frameworks based on the market. In addition to that, strict testing, risk analysis, and documentation are necessary to ensure compliance and show that the packaging materials fulfill food safety regulations while offering the desired intelligent functions.

Economic and technical obstacles stand in the way of the expansion of intelligent packaging systems, especially those that use cutting-edge materials like biosensors and nanocomposites. In technical terms, the manufacturing of biosensors and nanomaterials necessitates exact synthesis techniques to guarantee reliable performance, which might be difficult to duplicate on an industrial scale [339]. Another level of complication arises from maintaining the stability and functionality of biosensors over time, particularly in changing environmental circumstances [340]. Furthermore, research on integrating these materials into biodegradable packaging films while maintaining their sensitivity and reactivity is still in its early stages. Economically speaking, large-scale production is costly due to the high cost of raw ingredients like conductive polymers or nanocellulose as well as the specialized machinery needed to fabricate them [341]. Innovations in material processing, economical manufacturing methods, and supportive legislation to encourage the food industry's use of intelligent, sustainable packaging solutions will be necessary to overcome these obstacles.

Other challenges include issues with accuracy, longevity, and environmental impact when integrating sensors into traditional packaging materials [342]. Durability is crucial since sensors need to continue working for the duration of the product's shelf life, even in the face of changing conditions in the environment, such as humidity, temperature fluctuations, and mechanical stress during transportation and storage [342]. Maintaining sensor accuracy is also crucial, especially when looking for specialized freshness indications like microbial activity, pH variations, or gas emissions. Inconsistent or inaccurate readings may result in inaccurate food quality evaluations, which would undermine customer confidence in intelligent packaging. The environmental impact of adding sensors must also be considered, particularly when employing synthetic dyes or electronic components that could make the package less recyclable or biodegradable [343]. This problem can be lessened by creating biodegradable sensors using natural pigments or bio-based materials, which will preserve functionality while advancing sustainability. Achieving practical, scalable smart packaging solutions that improve food safety and cut waste without sacrificing environmental objectives requires striking a balance between these aspects.

Additionally, to address these challenges, it is crucial to enhance the resilience of intelligent packaging systems and integrate multiple packaging technologies to maximize their potential benefits [21,41]. Hence, another way that has been employed to overcome these challenges is through scalable fabrication techniques, such as roll-to-roll (R2R)

printing, which is revolutionizing the production of sensor-embedded films by enabling high-throughput manufacturing at reduced costs [344]. R2R printing is appropriate for creating large quantities of smart packaging materials with embedded sensors because it enables the continuous deposition of functional materials on flexible substrates [345]. By incorporating elements like circuits, conductive inks, and antennas straight onto packaging films, advancements in printable electronics can improve this strategy even more and open the door for RFID-enabled packaging [346]. Throughout the supply chain, these RFID tags may track products and provide real-time data on shelf life, storage conditions, and product authenticity [347]. The integration of colorimetric sensors, NFC tags, and QR codes is also supported by R2R approaches, allowing for interactive packaging that provides customers with real-time food quality information [345,348]. These developments enhance packaging functionality while preserving cost and sustainability for large-scale applications by fusing smart technologies with scalable printing techniques. Despite the challenges, intelligent packaging materials offer numerous advantages, such as optimizing the "first in, first out" approach, allowing retailers to prioritize the sale of products with shorter shelf lives based on their actual quality status [28]. This approach helps reduce food waste [337] and contributes to sustainability efforts by minimizing food wastage, optimizing energy consumption, and promoting better recycling practices [337]. Other techniques that can be explored to overcome these challenges include the identification and tracking networks and smartphone-compatible sensors.

7.1. Identification and Tracking Network

Traceability is an essential feature of intelligent packaging, contributing significantly to food safety and the streamlined management of supply chains. Innovations like QR codes and RFID (radio-frequency identification) are commonly utilized to track products' location and monitor conditions such as temperature and humidity across the distribution process [349]. Through the early detection of logistical problems, such as breaches within the chain of cold storage, this real-time monitoring helps to preserve food quality. Alongside these technologies, the rise in blockchain has introduced a stronger and more reliable solution for traceability [350]. Blockchain is a distributed, decentralized ledger technology that safely logs transactions in an unchangeable manner, ensuring that data remain permanent once they are entered [203]. This feature makes blockchain well suited for promoting transparency and building trust across the supply chain.

According to Singh et al. [351], blockchain can transform food safety traceability systems by allowing products to be tracked from farm to consumer, with visibility for all stakeholders to increase trust in data integrity. Additionally, by integrating technologies like RFID and the IoT (Internet of Things), blockchain facilitates the real-time tracking of food conditions, enhancing data accuracy and responsiveness in the event of supply chain disruptions. Similarly, Yele and Litoriya [352] highlighted the effectiveness of blockchain in the restaurant industry for enhancing transparency and ensuring food safety through traceability. Integrating blockchain with IoT devices and smart contracts enables the real-time tracking of food ingredients, enhancing consumer trust in food safety practices [353]. RFID UHF technology has proven to be a valuable tool for food traceability, especially within the meat industry [354]. For example, Qiao et al. [355] developed a traceability system utilizing UHF RFID technology, which ensures precise data collection throughout every stage of meat production and distribution. This technology excels in extreme conditions and can read multiple tags simultaneously, improving tracking efficiency.

However, challenges such as scalability and interoperability still need to be addressed, as highlighted by Singh et al. [356]. Despite these obstacles, the potential of these technologies to improve safety and transparency in the food industry is clear, with ongoing research

crucial for overcoming these hurdles. Moreover, when combined with real-time monitoring technologies, these innovations improve data quality and facilitate faster responses to supply chain issues, offering significant potential for the future of intelligent packaging in compliance with regulatory standards.

7.2. Smartphone-Compatible Sensors

Sensors that work with smartphones, especially colorimetric indicators, are becoming useful instruments for tracking the freshness of food in real time due to their powerful processing power, mobility, affordability, and ease of use [357]. These sensors react to chemical changes—such as pH shifts, gas release, or microbial activity—that are linked to food spoiling by changing color. Additionally, these indicators can offer a visible freshness signal that is simple to identify with smartphone cameras and image analysis software by incorporating natural hues into biodegradable packaging materials [358]. Apart from this, biosensors demonstrate promising capabilities in delivering high sensitivity and analytical precision for detecting intricate food matrices [359,360]. Smartphones are among the most promising tools for on-site sensing, control, and analysis. By facilitating real-time, non-destructive monitoring without the need for specialist equipment, this technology improves customer involvement in food quality management. Smartphones, equipped with operating systems, multicore processors, internal storage, advanced transducers, communication modules, and high-resolution cameras, serve as highly capable devices that integrate functions of controllers, sensors, monitors, and even data processors [358]. Due to its versatile built-in functional modules, a smartphone can function either as a standalone device or be paired with additional accessories in various sensing systems [361,362]. For example, the high-definition cameras in smartphones have been extensively utilized to study colorimetric and fluorescence assays for applications in healthcare diagnostics, environmental monitoring, and food quality assessments [363–365]. It provided an easy-to-use approach for creating portable detection systems. Given the widespread use of the mobile internet, smartphones equipped with disposable sensors can revolutionize traditional professional testing by enabling fast, real-time detection that anyone can perform anytime and anywhere [358]. The widespread use of smartphones will significantly expand the range of portable devices available for food evaluation. Smartphones are the perfect analytical tools for on-site sensor systems because of all their features. Furthermore, the creation of smartphone-compatible sensors meets the increasing need for smart packaging solutions that enhance food safety, minimize waste, and foster sustainability.

8. Conclusions and Future Directions

In conclusion, this review has highlighted the recent advancements in the use of intelligent packaging as a promising solution to addressing the global food security crisis. Numerous studies discussed in this paper underscore the potential of cutting-edge technologies and innovative materials to revolutionize food preservation. Active and intelligent packaging solutions, including the integration of sensors, nanomaterials, and other intelligent features, have shown significant potential in extending the shelf life of food products while maintaining their safety and quality. A crucial aspect of these advancements is sustainability, with smart packaging solutions aiming to reduce waste and minimize environmental impact through innovations such as biodegradable materials and optimized packaging designs. However, despite these promising developments, the substantial costs associated with the operation, production, and technical complexities of intelligent packaging remain significant barriers to its widespread adoption in the food industry. The limited adoption of intelligent packaging in the food industry stems from challenges like high costs, technical complexities, and regulatory hurdles, but these obstacles can be overcome with

focused research and collaboration among researchers, industry leaders, and policymakers. Integrating Artificial Intelligence (AI) and the Internet of Things (IoT) into packaging systems offers transformative potential by enabling the real-time monitoring of critical factors such as temperature, humidity, and gas composition. Predictive AI models can analyze these data to anticipate spoilage, detect quality degradation, and forecast shelf life, helping supply chains reduce food waste, improve storage conditions, and ensure fresher products. Additionally, sustainable solutions like recyclable, sensor-embedded materials—such as RFID tags on biodegradable substrates—can revolutionize waste management by providing real-time lifecycle data, enhancing recycling efficiency and reducing contamination in waste streams. This approach not only supports circular economies but also fosters a more sustainable, efficient food system where resources are conserved, waste is minimized, and intelligent packaging drives both environmental and consumer benefits.

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