Trends in Smart Packaging Technologies for Sustainable Monitoring of Food Quality and Safety

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Trends in Smart Packaging Technologies for Sustainable Monitoring of Food Quality and Safety

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***Abstract*: Food packaging has a significant impact on food preservation, thus prolonging the shelf-life and maintaining sustainable food quality and safety throughout the food supply chain and even during storage. Consumer desire for reliable, sustainable, organic, healthy, and unique products with "clean" labeling has risen as a result of technological advancement. Food packaging innovation is mainly described by the advancement of smart packaging technologies such as active and intelligent packaging. Active packaging is the use of active ingredients in more sustainable packaging materials to expand storability while ensuring product safety and quality. Intelligent packaging systems are developing to become more economical, efficient, and integrated matrices to deliver new packaging ideas that maintain the state of the packed food to deliver information on the product quality during shipping and storage. This review will provide a detailed overview of recent significant advancements and trends in the evolution of smart packaging.**

***Keywords*: Sustainable, Safety, Smart packaging, Shelf-life, Intelligent packaging**

I. INTRODUCTION

Food packaging is aimed to give food items consistent quality and long shelf life through containment, storage, communication, transportation, marketing, efficiency, and end-use [1]. It functions as a shield against the surrounding environment, preserving food safety and quality from the supplier to the end-user. Packaging usually includes details regarding the composition of food, nutrient profile, storage guidelines, calorie count, labels, manufacturer, expiry dates, type of materials, structure, reliability, color, and volume of the substance, etc. [2], [3]. Furthermore, packaging may be used to detect and communicate the changes in the physicochemical properties (e.g., respiration, pH changes, oxidation, discoloration), microbial infestation, and spoilage [4].

Due to the accumulation of food packaging waste, consumers choose more environmentally friendly, sustainable food packaging alternatives to traditional petroleum-based packaging. In this regard, paper-based packaging is expanding at a compound annual growth rate of 3.41%. Novel methods have been developed to produce lightweight biodegradable packaging materials, eg., the addition of lignin containing micro/nano-fibrillated cellulose into paper [5].

According to Kuswandi et al. [6], food degradation is frequently caused by oxidation and microbial development in food, resulting in food deterioration and loss of freshness. Furthermore, food degradation can be caused by enzyme processes, nonoxidative activity, moisture loss or uptake, flavors and odors, light exposure, etc. [7]. There is wastage of around 1/3 of global food production annually [8]. Currently, a population of 7.6 billion generates almost 1.3 billion tons of food waste globally [8]. Therefore, food processing technologies and practices should be evaluated and improved in order to decrease food waste.

Furthermore, foodborne diseases are now mostly caused by microbial contaminants in food. Because the lethal microorganism *L. monocytogenes* grows at lower temperatures (2-4 °C), it may be found in readily available food items with a longer storage life, including processed fish and meat products, cheese, etc. [9]. According to World Health Organization (WHO), more than 600 million incidents of disease are connected to unsafe and unsecured food supply each year, with over 400,000 people dying from food-borne infections. Nevertheless, foodborne infections are still a serious cause of illness and death in many developed nations each year.

Furthermore, significant changes in the supply chain linked to globalization cause substantial food quality and safety concerns. Traditional packaging seeks to reduce food product exposure to harmful environmental factors, but it is frequently insufficient. It's challenging to keep control and maintain the highest possible quality throughout the entire production process and storage. This situation presents the packaging sector with a tremendous chance to produce novel technologies to satisfy the varying industrial and consumer requirements, as well as growing legal and regulatory needs.

Innovative packaging concepts, particularly smart food packaging, are a new technology aimed at reducing wastage while maintaining the health and safety of consumers. This will help to optimize the food supply chain and consumer consciousness of food utilization, as well as improve food storability and develop connections between producers and end-consumers, all while preserving food quality [10].

II. THE CONCEPT OF SMART PACKAGING

Natural polymers such as polysaccharides, lipids, proteins, and resins or synthetic polymers such as polyethylene, polyamide, polypropylene, aluminium, polyvinylidene chloride, etc. are used in the development of food packaging [1]. Among natural polymers, cellulose-based packaging is extensively used in the food industry. Novel and innovative methods have been developed in the application of cellulose nano fibrils due to their excellent mechanical and barrier properties, and high biocompatibility [11]. In addition, lignocellulosic fibers, which are produced using a simple, low-cost, and ecofriendly procedure, generate high yield and good texture, being barrier for chemical modification, and are used in efficient and sustainable food packaging [12]. But, due to their poor dispersibility in hydrophobic substrates and limited resistance to water vapor permeation, their mass applications are frequently limited.

Smart packaging is one of the innovative alternative technologies that suggests overcoming various issues. Smart packaging technology may be categorized into 2 groups in terms of its overall function: active packaging and intelligent packaging. Active packaging techniques provide active protection by prolonging the storage life and enhancing the quality, and intelligent packaging systems indicate the product quality and communicate with the consumer along the distribution and supply chain [2], [13]. Smart packaging confirms integrity, authenticity, and performs an active function to prevent spoilage. It may also enhance food attributes such as taste, appeal, and visual appearance, communicate the additional information about the food to the consumer, and adopt to changes in food structure or the packaging environment [3], [14].

Active packaging has the ability to interact with the food, package, and its headspace to extend shelf life and/or improve sensorial properties and safety while retaining the packed food quality [15]. It satisfies market needs for high-quality, safe, and fresh-like products by creating a barrier to outside forces and regulating and responding to changes within the package to preserve food quality [16]. Intelligent packaging may extend storage life, improve food security and quality, provide information and facts, and alert users about potential issues [17]. It's a novel concept that uses either the external (humidity, gases, temperature) or internal (metabolites, etc.) packaging conditions as "data" to provide biosafety, accessibility, or to manage a food product for instant product identification and traceability [15]. Figure 1 depicts the technologies of smart packaging and categorization, and their contributions to food quality and safety improvement.

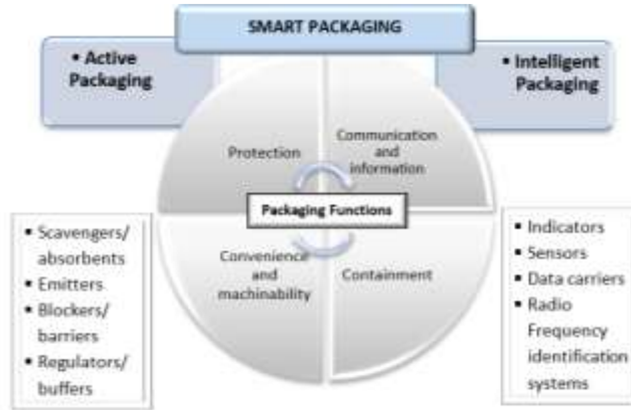

Fig. 1. Technologies of smart packaging, their classification, and food packaging

This review focuses on providing a broad update of the most recent advances in smart packaging in the form of active and intelligent packaging that contribute for the sustainable monitoring of food safety and quality for their future applications [9].

III. ACTIVE FOOD PACKAGING SYSTEMS

The term "active food packaging" was initially applied by Labuza (1987) [18]. Active packaging is the intentional inclusion of different additives or ingredients into packaging film or packing units to maintain, prolong product shelf life, and optimize package system performance as described by the European regulation (EC) No 450/2009 [19]. Furthermore, active packaging may be defined as a technique that has served to reduce the rate of respiration, microbiological development, moisture migration, and oxidation with the major intent of enhancing safety, quality, shelf-life, and freshness of foods [9].

The concept behind active packaging is focused on the properties of the polymers used in the packaging itself or on the surface of multilayer structures, or on the inclusion of particular compounds within the polymeric material [20]. Active packaging has the objective of avoiding microbiological infestation, reducing undesirable biochemical reactions, and preserving the optical and sensory characteristics of packed food [10]. Substances capable of absorbing moisture, carbon dioxide, oxygen, ethylene, aromas, or flavors, as well as compounds capable of emitting carbon dioxide, preservatives, flavors, antioxidants, and antimicrobials, might be included in active packaging structures [21]. Active packaging technology has led to advancements in a variety of fields, including the controlled rate of respiration in horticultural products, delayed oxidation in muscle foods, delayed microbial development, and moisture migration in dehydrated or dried products [21]. Furthermore, active packaging involves coating, lamination, co-extrusion, polymer mixing, or micro-perforation to regulate selectivity in order to change the concentration of gases at ambient levels inside the package [22].

There are four different forms of active packaging applications being used in the food sector [4]:

i. Active scavengers or absorbers
ii. Active releasers or emitters
iii. Barrier or blocking agent, and
iv. Regulating or buffering

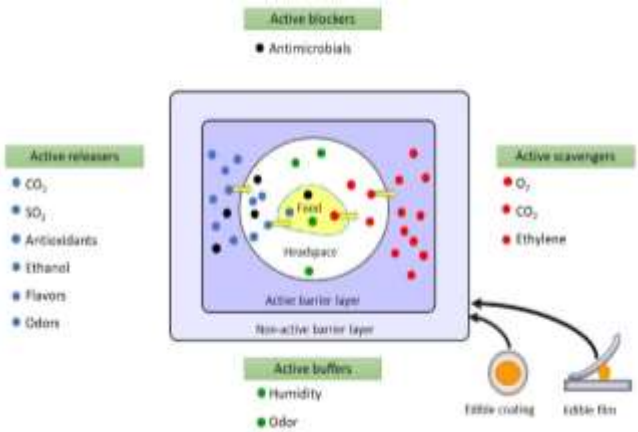

Figure 2 demonstrates the schematic representation of active food packaging systems.

A. Active scavengers and absorbents

Gases including O_2, CO_2, and ethylene are removed from food packaging using active scavenging technologies. Furthermore, by using absorbents such as O_2, CO_2, and ethylene as active packaging systems in modified atmospheric packaging (MAP), it is possible to enhance the storability of foods and maintain the freshness of minimally processed or fresh-cut vegetables and fruits [4].

1) Oxygen scavengers - Oxygen scavengers (OS), which attempt to eliminate any excess oxygen available in the food package or to optimize barrier qualities by functioning as an active shield, are one of the most frequently used active packaging technologies [9], [23]. Foods that are susceptible to oxygen, can promote oxidative degradation and changes in flavor, odor, or color as a result of enzymatic and chemical processes that can degrade quality [24]. The oxidation of lipids, vitamin E, ascorbic acid, colors, and certain amino acids, as well as the development of aerobic bacteria, are all caused by oxygen [25],[26]. This results in the generation of off-odors and off-flavors [24], sensory alterations [27], nutritional losses [28], and has a considerable impact on the overall shelf-life stability of muscle food products [29]. To avoid its negative effects, the residual oxygen level has to be reduced. Consequently, controlling the levels of oxygen in food packaging is crucial for preventing food spoilage reactions. It may be accomplished by using oxygen scavengers [30], which can lower the oxygen content in the headspace to less than 0.1 vol.% [31]. Oxygen scavengers can be used as labels, sachets, films, or cards, or they can be inserted into the package [29]. Research revealed that oxygen scavengers can preserve both fat and water-soluble vitamins [29] and are effective in avoiding rancidity in foods, discoloration in tea, and mold spoilage in high-moisture bakery products, and minimizing the oxidative flavor of coffee that changes its taste [4]. By removing O_2 completely from the food package, it can increase the shelf-life of seafood [4]. When spoilage induced by O_2 is the main reason for quality losses, controlling O_2 by using oxygen scavengers has a number of economic benefits, including lower food losses and returns, expanded distribution circle, customer and brand loyalty, reduced artificial food additives in the formulation, and reduced production costs [15]. Recently developed oxygen scavengers are commonly focused on the iron powder oxidation (e.g. ferrous carbonate, powdered iron oxide, metallic platinum) [24], [32], ascorbic acid oxidation [32], enzymatic oxidation (e.g., alcohol oxidase and glucose oxidase) [34], photosensitive dye, catechol, ferrous carbonate, oxidation [35], unsaturated fatty acids (e.g., linolenic or oleic acid) [33], or immobilized microorganisms on a solid substrate [36]. Recent applications of oxygen-scavenging food packaging systems are listed in Table I.

Table I. Trends In The Use Of Oxygen-Scavengers In Food Packaging Applications

Active substance	Matrix/ packaging	Food application	Significance	Reference
Iron	Multilayered carton: PP/EVOH/OS/PP	Meatballs	Significant inhibition in the oxidation of lipids and inhibition of change in color and flavor over a 9-month storage period	[37]
Photosensitive dyes	$ZerO_2^{TM}$ OS-laminated film: OPET/EVOH/OS/CPP	Milk	Inhibition of musty flavor development	[35]
Ascorbic acid	LLDPE-films incorporated with iron or zinc-powders and ascorbic acid	Bread slices and bun	Extension of storage life, retardation of microbiological development up to 2-5 days, improvement of sensorial acceptance from 2 to 5-6 days	[38]
Unsaturated hydrocarbon dienes	PET film, cast extruded OS: AMOSORB ™	Banana fresh-cuts	Decline in browning discoloration: After 3 days, there was around a 50% reduction in color difference	[39]

Some commercial oxygen-scavenging solutions are AGELESS OMAC® (OS-film, Mitsubishi Gas Chemical Inc., USA), PolyOne™ (Europe Ltd., Liverpool, UK.), SHELFPLUS® O_2 (OS-masterbatch, Delaware, USA), Cryovac® (OS film, Sealed Air Corporation, USA), and OxyRx® (OS-containers, Mullinix Packages Inc., USA [29].

Fig. 3 AGELESS® (OS-film, Mitsubishi Gas Chemical Inc., USA) [26]

2) CO_2 scavengers **-** CO_2 is a byproduct of catabolic activities in biological systems, and its content inside the food package can be elevated owing to fermentation, respiration, and browning reactions in particular foods [16]. For instance, non-enzymatic browning processes in roasted packed coffee beans can release up to 15 atm of dissolved CO_2, resulting in alterations in product flavors and aromas as well as the development of undesired anaerobic glycolysis in fruits [15], which can cause the package to burst [10]. Fermented products such as sauerkraut, sauces, pickles, and some dairy products such as yogurt and cheese [40] can produce CO_2 after the process of packaging due to their microbial activity [16]. Excess CO_2 production can cause collapse or unfavorable changes in food texture and flavor, as well as browning discoloration, off-flavor generation, and tissue degradation in foods including potatoes, lettuce, carrots, onions, cauliflower, peaches, and apples [26].

Scavengers of CO_2 are included into the food packaging as sachets for items that undergo aging processes and fermentation after they have been packaged to overcome this excess CO_2 accumulation and the limited permeability of some packages to CO_2 [15]. In general, hydrating agents such as silica gel and calcium oxide packed in porous sachets allow water and calcium oxide to react to make calcium hydroxide, the active CO_2 scavenger compound that combines with CO_2 at elevated humidity levels to produce calcium carbonate within the package [41]. Other scavengers consist of potassium hydroxide, sodium hydroxide [7] in the form of granules or sachets, activated carbon, and zeolites as physical absorbers in the form of beads or powder [26]. Using a blend of sodium chloride, bentonite clay, sodium carbonate, and sodium carbonate peroxyhydrate with two distinct compositions, new commercial dual-action O_2 emitting and CO_2 scavenging sachets have been produced to overcome the problems in respiration in the active MAP of strawberries, fresh-cut vegetables, and fruits [42]. In addition, customized CO_2 and O_2 scavengers were developed for single-use instant coffee containers [43].

3) Ethylene scavengers **-** Ethylene is a phytohormone that is released after fresh produce is harvested. It has many physiological effects on fresh vegetables and fruits, such as initiating and accelerating ripening, which leads to maturity and senescence, degradation of chlorophylls, and softening, which results in loss of quality [44]. Furthermore, the yellowing of green crops caused by significant ethylene accumulation might be the cause of a variety of postharvest diseases [45]. To maintain the postharvest freshness, quality, and organoleptic properties of the fruits and vegetables, the accumulation of ethylene within the packaging should be avoided [33]. Ethylene scavengers are packaging systems that remove ethylene from the surrounding environment of fresh vegetables or fruits, slowing the ripening and degradation processes and improving the post-harvest quality of crop products [16].

The most common ethylene scavenging method is to utilize potassium permanganate ($KMnO_4$) in the form of highly permeable pouches for blankets and packages that can be positioned in product storage chambers without interacting with food packing material [46]. Clay, alumina, silica, vermiculite, activated carbon, and other inert porous support materials are used to immobilize $KMnO_4$ [18]. The mechanism is that $KMnO_4$ has the potential to oxidize ethylene to acetate ethanol, changing color from purple to brown in the process, indicating its residual ethylene absorption capability [47]. Some other systems can absorb ethylene alone or with an oxidizing agent (e.g., minerals including silicates, zeolites, pumice, activated carbon, etc.). Table II provides information on trends in ethylene scavenging systems for food applications. The prevention of accumulating ethylene and reduction of the softening rate in bananas, tomatoes, and kiwifruits, and loss of chlorophyll in green vegetables can be effectively achieved by the use of palladium with charcoal [48]. Metal oxides, for example, photoactive TiO_2 and nano-TiO_2, are also reported to oxidize ethylene [27]. Instead of the packaging structure, absorbent pads made with nano-silver that act as an ethylene blocker have been installed in trays of fresh-cut melon [49].

Table II. Trends In Ethylene Scavenging Systems For Food Applications

Scavenging substance	Application form	Food application	Significance/ benefits	Reference
Vermiculite	Sachets	Sapodilla	Reduction of firmness loss of pulp and degradation of vitamin C at 25 °C and 54% RH for 5 day-storage period	[46]
TiO_2	Chitosan film	Tomatoes	Delayed the quality deterioration of the tomatoes due to the ripening process and 25 °C and 50% RH storage	[50]
Nano-silver	Absorbent pads	Fresh-cut melon	Affected ripening by inhibiting ethylene-mediated ripening mechanisms, resulting in a less ripe/juicier product	[49]
Silica crystals	Sachets	Guava	Delayed changes in fruit firmness, total soluble solids (TSS), titratable acidity (TA), and color, reduced decay when stored at 8 °C	[51]

B. Active emitters

1) CO_2 emitter - Higher CO_2 concentrations (10-80%) are beneficial in effectively reducing the growth of microbes on food surface and so prolonging the storability of food items, including fresh fish, meat, poultry, cheese, or baked dishes, due to their bacteriostatic and fungistatic effects [9], [52]. However, a higher content of CO_2 can stimulate the development of yeast and lactic acid bacteria [52]. The CO_2 emitters have been used since 1990 as active packaging solutions in MAP to impart an antimicrobial effect. For meat and poultry preservation in MAP, CO_2 emitters are widely used in to replenish the CO_2 losses that occur due to dissolution into the meat and avoid the collapse or formation of a partial vacuum in flexible packaging due to permeation through the polymeric packaging material [30].

CO_2 emitters are frequently used in conjunction with an oxygen scavenger and may appear in the shape of a pad, sachet, or label device [16]. They contain iron carbonate (II), blends of ascorbic acid or citric acid, sodium bicarbonate, and metal halide as a catalyst to obtain a CO_2-releasing system [26], [30]. The active compounds within the pad react when liquid seeps out of the product, releasing CO_2 [53]. One of the most common CO_2 emitters has recently been developed on the basis of active ingredients like sodium bicarbonate and citric acid [54]. This was applied in conjunction with MAP to investigate the effect on quality attributes of cod loins (*Gadus morhua*) [55]. Using a CO_2 emitter extended the shelf life in MAP with low headspace volume by 2–4 days, while increasing CO_2 levels enhanced quality preservation. The CO_2 emitters have a variety of commercial applications including CO_2 Freshpads (CO_2 Technologies, USA), Active CO_2 pads (CellComb AB, Sweden), SuperFresh (Vartdal Plastindustri AS, Norway), UltraZap® XtendaPak (Paper Pak Industries, USA), and FreshPax® type M (Multisorb Technologies), Ageless™ type G (Mitsubishi Gas Chemical Co., Ltd.) [56],[57], which are dual-action CO_2-releasing and O_2-scavenging sachets.

2) *Ethanol emitter* **-** The spraying of ethanol, a widely recognized germicidal agent, just before the packaging of food products surfaces, such as intermediate moisture foods, cheese, bread, cookies, biscuits, and other bakery products, is successful in prolonging the shelf life of foods by inhibiting the development of yeast, mold, and bacteria [1], [58], [59]. Though it has been claimed that spraying bakery items with 95% ethanol will greatly prolong their mold-free shelf life, ethanol-emitting films and sachets are a more practicable and healthier way to generate ethanol [60]. The advantage of this is that ethanol vapor is instantly emitted from ethanol-releasing sachets within the package, preventing ethanol from coming into direct contact with the food and hence delivering safer foods than ethanol spraying prior to packaging [61]. Once the food product is packaged including an ethanol-emitting sachet, ethanol vapor is slowly or rapidly emitted and dispersed into the package headspace. The emitted ethanol vapor condenses on the surfaces of the foods and functions as a microbial inhibitor [50], eliminating the requirement for other preservatives such as propionates, benzoates, and sorbates [58].

In addition to ethanol, some sachets or films may contain flavors such as vanilla in trace amounts, which comes under the commercial name of Ethicap®, an active ethanol emitter (Freund Company Ltd. of Japan) [60]. This sachet is widely used for a variety of bakery items, semi-dried fish, cheese, and poultry products [53]. A study conducted on packed prebaked buns employing an Ethicap® ethanol emitter revealed that yeasts and molds were significantly eliminated in prebaked buns stored at room temperature [60].

Molds such as *Penicillium* and *Aspergillus*, as well as bacteria including *Escherichia coli*, *Staphylococcus*, *Salmonella*, and spoilage yeasts can all be controlled by ethanol emitters [53]. Ethanol emitters are frequently used in Japan to keep high-ratio cakes and many other high-moisture baked items mold-free for longer periods of time [18]. Many other commercial applications of ethanol emitters have been developed, particularly by Japanese companies, including Antimould 102™, ET Pack™ (Ueno Seiyaku Co. Ltd.), Oitech™ (Nippon Kayaku Co. Ltd.), and Ageless® type SE (Mitsubishi Gas Chemical Co. Ltd) and Negamold™ (Freund Industrial Co.), which are dual-action oxygen scavenging and ethanol vapor emitting sachets [30], [62].

1) *SO_2 emitter* - SO_2 incorporated into the packaging material as metabisulphite salts is the most common volatile antimicrobial substance used for fresh fruit products because of its high efficiency as a fungicide [63]. The activity of SO_2 emitters is often dependent on the hydrolysis of metabisulphite and the interaction of calcium sulfite with moisture [4]. For pineapple packaging, sulfur dioxide emitters have now been utilized to inhibit mold growth by releasing antifungal substances into the package headspace [64]. Youssef et al. [65] analyzed the impact of several forms of SO_2-generating pads on the development of gray molds and physicochemical attributes of the 'BRS Nubia' seeded grape variety and revealed the best type of SO_2-generating pads for minimizing gray mold in table grapes while retaining fruit quality. The application of SO_2 to blueberries, which are highly susceptible to postharvest decay, has been proven to successfully minimize deterioration over prolonged storage [66]. The blueberries were packed in SO_2 emitting sheets under MAP conditions. When combined with a modified atmosphere (MA), the SO_2-emitting liners were efficient in decreasing biological degradation and the development of aerial mycelia of *Botrytis cinerea* from infected berries relative to treatments without SO_2.

2) *Antioxidant releasers* - Oxygen may be unfavorable to food items, causing lipid and protein breakdown, which results in the generation of off-odors, off-flavors, and color discoloration of food [67]. Products high in fats and oils, such as cheese, nuts, crisps, chocolate, processed fish, and meat, are particularly susceptible to oxidation, resulting in a decrease in storability due to the variations in odor and/or flavor, a reduction in the functionality and texture of muscle foods, and a loss of nutrient value [68]. The use of antioxidants and oxygen scavengers in the packaging may contribute to the prevention of oxidation by eliminating radicals, which are initiators of oxidation as soon as they are formed [9].

The additives which are gaining increased attention in the exhibition of antioxidant properties are natural antioxidants such as vitamin C, E (α-tocopherol), natural extracts, essential oils (ginger, rosemary, clove, lemongrass, oregano, cinnamon, green tea, black tea, etc.) [33], [69], [70], and spices such as flavonoids and phenolic acids [71]. In addition, butylated hydroxyanisole, butylated hydroxytoluene, propyl gallate, and tert-butylhydroquinone are used as synthetic antioxidants in food production [16].

Through the insertion of butylated hydroxytoluene into LDPE packaging, Torres-Arreola et al. [72] discovered a delay in protein denaturation and lipid oxidation, as well as suppression of tissue damage and greater firmness retention in fresh sierra fish fillets. Because butylated hydroxyanisole and butylated hydroxytoluene are more volatile than α-tocopherol, it is proposed that the application would be better suited for dry food applications, whereas α-tocopherol delivered equivalent antioxidant protective effects for whole milk powder exposed to light and oxygen [73]. Moreover, the synthetic antioxidants usage might cause safety issues due to their carcinogenicity [74]. Food processors are increasingly interested in incorporating natural antioxidants as substitutes for synthetic antioxidants.

Packaging consisting of polyvinyl alcohol (PVA)-based films impregnated with clove essential oil exhibited significant antioxidant activity, inhibiting lipid oxidation and bacterial growth in ribbonfish (*Trichiurus haumela*) [75]. A study done earlier by Navikaite-Snipaitiene et al. [76] on the development of antioxidant packaging for beef using cellulose acetate or acrylic component/hydrophobically modified starch incorporated with eugenol and clove essential oil has shown decreased oxidation of lipids and protection of the beef color. López-de-Dicastillo et al. [28] tested the antioxidant properties of films to prevent oxidation of lipid in brined sardines. The film containing green tea extract was the most effective in terms of antioxidant activity among the ethylene-vinyl alcohol (EVOH) copolymer-based films made by combining green tea extract, ascorbic acid, ferulic acid, and quercetin. The natural flavonoid quercetin incorporated EVOH-based active film exhibited better stability in lipid oxidation during storage, as evidenced by a decreased peroxide index and a 25% decrease in thiobarbituric acid reactive substances (TBARS) levels. An improved oxidative and color stability was recorded in pork sausages by the application of chitosan film incorporated with green tea extract using the solvent casting technique [77]. It was shown that employing active packing materials with oregano and rosemary extracts in contact with muscle foodstuffs increased the oxidative stability of beef and lamb meat while preserving their fresh odor and color [69], [70]. Furthermore, the antioxidant-rich active packaging can be applied to oil, nuts, butter, poultry, seafood, bakery products, vegetables, and fruits as listed in Table III.

5) Release or absorption of flavors and odors - Flavor scalping occurs when food packaging polymeric materials interact with the flavors of the food they hold, resulting in flavor loss, alterations in the organoleptic qualities, and taste intensities of the food [58]. Also, food processing at higher temperatures leads to flavor loss or degradation. Volatile compounds including aldehydes, sulfides, and amines, may accumulate within the package and become detrimental to food quality. Therefore, there is a need to restore the flavor components that have been lost due to scalping or deterioration. This can be effectively and successfully achieved by the application of odor and flavor absorbers as active packaging to absorb undesired odors or flavors selectively [84]. Odor and flavor absorbers are usually available in the form of sachets, films, labels, trays, or tapes, and are positioned directly within packages or integrated with flavor-permeable substances. They can be used to remove unpleasant flavors and aromas caused by metabolic and oxidative processes that occur during food degradation [61]. These odors and flavors are gently and evenly released in the packed food over its shelf life or released into a controlled manner during package opening or preparation of food [85].

Morris [86] developed an odor-proof packaging system for transporting durian fruits. The package is comprised of a sealable container formed from an odor impermeable material like polyethylene terephthalate (PET) or polyethylene, the container having a gas permeable terminal to enable the movement of respiratory gases, including an odor-absorbing material in the form of a pouch made of nickel and charcoal mixture. The package has applicability to any situation where odors given off by fresh produce must be contained, and movement of fresh air into the container is also required. Certain orange cultivars, such as Navel, may develop a bitter flavor due to the high limonin content released due to chemical reactions in the acidic pulp matrix. To address this, a thin cellulose acetate butyrate layer has been created for use within the packaging that acts as limonin absorbers and has been proven to significantly minimize the bitterness in freshly processed citrus juices, hence prolonging shelf life [87]. Non-polar flavor absorption can be prevented by using polar plastics, high barrier packing materials, or corona treatment of the film surface [22]. The foul-smelling volatile amines generated by protein metabolism in fish flesh could be eliminated by including acidic substances such as citric acid into polymers [21]. The ANICO bag, supplied by Anico Co. (Japan), is a film composed of ferrous salt and an organic acid, including citric acid or ascorbic acid, that has the potential to oxidize amines or other oxidizable odor-causing substances after they have been absorbed by the polymer [61].

Table III. Trends In Antioxidant Releasers For Food Packaging

Active substance	Matrix/ packaging	Food application	Significance	Reference
Mango kernel extract	Soy protein isolate (SPI) and fish gelatin	Palm oil	Color and oxidative stability improvement	[78]
Green tea extract and oregano essential oil (EO)	Multilayer film: PET/PE/EVOH/PE	MAP foal steaks (Longissimus dorsi)	Improved color and oxidative stability by reducing the production of metmyoglobin and TBARS	[79]
α-Tocopherol	LDPE film	Corn oil	Improved oxidative stability due to low hexanal content	[80]
Ascorbic acid	Alginate-based coatings and films	Fresh-cut papaya	Improved oxygen barrier properties and increment in ascorbic acid content during the storage	[81]
EO from Ocimum basilicum L, Rosmarinus officinalis L., Mentha pulegium L.	Alginate-based film	Cheese	Improvement of oxidative stabilities of proteins and lipids	[82]
Quercetin, catechin	EVOH film	Sunflower oil, fried peanuts	Improved oxidative stability due to lower hexanal content	[28]
Citric acid	Alginate-based films and coatings	Sliced carrots	Together with MA, shelf life was enhanced by improving oxidative stability	[83]

C. Antimicrobial packaging

Microbial contamination caused by pathogenic or spoilage bacteria is one of the key factors affecting the decline in quality and the reduction in shelf-life. Microbial growth in foods can lead to spoilage or food-borne infections, resulting in a loss of color, texture, flavor, and safety, and accelerate the generation of food waste, causing economic losses [88]. The development of antimicrobial packaging is an effective strategy in the smart packaging concept to actively control microbial growth [56]. This helps in the preservation of the packaged food while retaining its safety and quality [15].

Antimicrobial activity in packaged food can be acquired by the inclusion and immobilization of antimicrobial agents, as well as surface modification and surface coating [16], and if they are non-volatile, they must have direct contact with the food surface. Antimicrobial agents come in 2 types [58]: chemical and natural preservatives. Examples of chemical preservatives that may be employed in active antimicrobial packaging are parabens, organic acids and their salts (mainly propionates, benzoates, lactates, and sorbates), sulfites, phosphates, chlorides, nitrites, hydrogen peroxide, anhydrides, alcohols, epoxides, diethylpyrocarbonate, ozone, bacteriocins, and antibiotics [58]. Because of the carcinogenic and mutagenic effects of chemical preservatives and their residual toxicity, the use of natural sources of antimicrobials for preserving food is becoming more popular, owing to consumer concerns on natural foods and growing fear about microbiological resistance to chemical preservatives. Natural antimicrobial agents that can be used in edible coating and film preparation comprise essential oils (lemongrass, clove, cinnamon, thyme, oregano, rosemary, ginger, etc.),seed extracts (grape and lemon), plant extracts (garlic, onion, mustard, radish, and horseradish), and antimicrobials produced by fungi and bacteria (natamycin, nisin, polypeptide), and various bacteriocins [89], [90].

Films incorporated with antimicrobials might be used in a range of commercial food applications such as fish, meat, processed meat products, poultry, cheese, bread, fresh vegetables, and fruits, particularly those with smoother surfaces. Recent developments in antimicrobial food packaging applications are listed in Table IV.

There are two types of active antimicrobial films:

i. Those that include antimicrobial compounds that migrate to the food surface and
ii. Those that have effective antimicrobial activity without active compound migration to the surface of the food [89].

1) Migrating system - Thorough studies on direct contact migrating antimicrobial packaging have focused on integrating antimicrobial additives into packing materials or coating food surfaces with antimicrobial coatings. Quaternary ammonium salts, copper ions, and natural substances for example Hinokitiol are widely regarded as safe antibacterial compounds [16]. Silver substituted zeolite has been the most commonly used antibacterial compound in plastic polymers in Japan [21], [31], [88]. Some examples of silver-substituted zeolites that are available commercially include Apacider®, Zeomic®, Novaron®, Biomaster®, AgIon®, Irgaguard®, Bactiblock®, Surfacine®, d$_2$p®, and IonPure®, Biomaster® [7], [47]. Food-touch® (Microbeguard Corp.) is paper with antimicrobial properties comprising AgIon® silver-based additive (Sciessent LLC) and is used as wrappers in active packaging of fresh fish fillets [7].

Potassium sorbate was used as an active antimicrobial agent in chitosan-coated plastic films to retard or inhibit L. *monocytogenes* and total aerobic mesophilic bacteria growth in ham steaks, cold-smoked salmon, and chicken drumsticks, and the films showed excellent long-term anti-listerial effects [91],[92]. Foralosso et al. [93] used PVC films with a 1:1 combination of encapsulated and pure potassium metabisulfite as an active antibacterial agent for minimally processed apples (*Malus domestica*) kept at 30% RH. It was reported that apple slices covered in PVC films with 1% (w/v) and 2% (w/v) potassium metabisulphite preparations were able to achieve a shelf-life extension of 4-8 days when kept at 8 °C.

Present approaches contribute to the potential application of antimicrobial compounds in packaging solutions for a wide range of food items due to their perceived lower risks to consumers. Essential oils (EO) have long been known for having antimicrobial effects against a diverse range of microbes, including pathogenic bacteria. Multilayer packaging material containing cinnamaldehyde as the main constituent of cinnamon essential oil (CEO) applied to tomato puree has shown effective inhibition of *S. cerevisiae* and *E. coli* O157: H7 [94]. In a study conducted by Arfat et al. [95], it was reported that the basil leaf essential oil-incorporated fish protein isolate/fish skin gelatin-ZnO nanocomposite film had a synergistic antimicrobial effect (12 days of shelf-life extension) against lactic acid bacteria, psychrophilic bacteria, and microbial pathogens when applied through indirect contact with sea bass slices. Further, Lee et al. [96] revealed that crab sticks packed with 0.05% vanillin incorporated starfish gelatin films presented an effective antimicrobial activity against *L. monocytogenes*.

Polymers with inherent antimicrobial activity such as chitosan, polylysine, polyethylenimine, and polyguanidines are employed in coatings and films. Chitosan is used as an edible packaging material in the form of film or coating to impart antifungal activity in fresh fruits and vegetables, as well as a shield between the microorganisms and nutrients in the food product [97], [98].

The development of active nano-food packaging technologies employing nano-composites combined with antimicrobials provides novel solutions to maintain food safety and quality during an extended storage period. For example, nanocomposite LDPE (low-density polyethylene) film containing carvacrol (as the antimicrobial agent) and organo-modified montmorillonite (MMT) (as a filler) was developed by Persico et al. [99], and it exhibited positive antimicrobial activity against *L. innocua*, *Carnobacterium* sp., and *B. thermosphacta*, excluding *Pseudomonas fragi*.

2) Non-migrating system - Some antimicrobial packaging systems are made by covalently immobilizing antimicrobial agents on solid supports to keep their inherent antibacterial activity while preventing bioactive ingredients from migrating into the core food [15].

Some non-migrating systems investigated include polymers containing biguanide compounds, quaternary ammonium, and phosphonium, enzymes (lactoperoxidase, lysozyme, etc.), bacteriocins (lactocin, nisin, subtilin, brevicin, pediocin, lacticin), UV irradiated nylon, reptile antimicrobial peptides like crocosin, and amphibian antimicrobial peptides like magainin [15], [100], [101]. Antimicrobial nanoparticles, mainly metal ions like copper, zinc, gold, silver, and metal oxides like titanium dioxide, magnesium oxide, zinc oxide, copper oxide, are used in various non-migrating antimicrobial food packaging applications such as chicken breast fillets, cooked rice, bread, fruit juices, poultry, cheese, etc. [30], [102]. Absorbent food pads embedded with lytic bacteriophages have also been suggested as a bio-control alternative packaging and a unique approach for extending the storability of chilled processed fish and meat [103]. Conte et al. [104], who investigated the efficiency of lysozyme immobilized onto the surface of PVA films, concluded that the viability of *Micrococcus lysodeikticus* was decreased by the immobilized lysozyme on PVA film. Higher antibacterial and antifungal activities were obtained by directly incorporating active lactoperoxidase into chitosan edible film as an active packaging for fruits like mangoes [108]. Sliced beef that was coated with palmitoylated alginate-based films immobilized with nisin, could efficiently control the growth of pathogens such as *S. aureus*, which is responsible for the spoilage at the surface of beef [109]. Furthermore, the application of bacteriocins and enzymes in conjunction with other preservation procedures results in the long-term preservation of fresh and minimally processed foods without any migration of active compounds into the bulk food [91].

Table IV. Trends In Antimicrobial Food Packaging Applications

Antimicrobial agent	Packaging application	Microorganisms tested	Food application	Significance	Reference
Essential oils					
Lemongrass EO	Alginate, sunflower oil/$CaCl_2$ edible coating (EC) matrix	Total plate count, yeasts, and molds	Fresh-cut pineapple	Significant reduction in the counts of yeast, mold, and total mesophiles, and extension of shelf-life	[107]
Thymol and carvacrol	Clay/polyethylene polymer nanocomposite	Gray mold (Botrytis cinerea)	Strawberry	Effective inhibition of B. cinerea with 1/3 of the total EO content, no substantial organoleptic change	[108]

Cinnamaldehyde	Chitosan reversible covalent immobilization	E. coli, Staphylococcus aureus, and L. monocytogenes in milk	Milk	Prolonged the shelf-life of milk, L. monocytogenes growth was inhibited for up to 12 days under refrigeration, and cinnamon odor was better accepted by consumers	[109]
Ginger EO	Whey protein isolate, sorbitol and alginate EC matrix	E. coli O157: H7 and S. aureus	Kashar cheese (semi hard cheese)	High bactericidal effect on S. aureus and bacteriostatic effect on E. coli O157: H7	[110]
Garlic EO	LDPE-based film	L.monocytogenes, E. coli, Brochothrix thermosphacta	Ready-to-eat beef loaves	Inhibition of L. monocytogenes growth on beef loaves at 4 °C for up to 15 days	[111]
Plant extracts					
Pomegranate peel extract	Alginate/$CaCl_2$ and chitosan EC matrix	Colletotrichum gloeosporioides	Capsicum	EC-pomegranate peel extract has antibacterial and antifungal properties and can be preserved at 10 °C for up to 25-day storage period	[112]
Grapefruit seed extract with lysozyme, nisin, EDTA	Alginate-based edible film (EF)	Gram-negative bacteria	Gram-negative bacteria contaminated foods	EF incorporated with EDTA or grapefruit seed extract provided effective antibacterial protection	[113]
Rosemary extract, bamboo leaf extract	Alginate/$CaCl_2$ EC matrix	Pseudomonas sp., H_2S-producing bacteria, Enterobacteriaceae, lactic acid bacteria	Abalone	Bacterial inhibition was improved by using EC-rosemary extract	[114]
Antimicrobial polymers [107]					
Chitosan	Chitosan-LDPE film	L. monocytogenes, S. enteritidis, E. coli	Fresh beef	Shelf-life extension of fresh red beef	[97]
Chitosan, glycerol	Chitosan/glycerol edible film	Gram-negative and positive bacteria	Strawberries	Excellent bactericidal and fungicidal activity, shelf-life extension for 7 days	[115]
Chitosan	Film made of chitosan, carboxymethyl cellulose, and zinc oxide nanoparticles	E. coli, S. aureus, C. albicans, P. aeruginosa	White soft cheese	Enhanced antifungal and antibacterial properties	[116]
Chitosan–tapioca starch/potassium sorbate	Chitosan–tapioca starch EC matrix	Lactobacillus sp., Zygosaccharomyces bailii	Sliced salmon	Effective reduction of aerobic mesophilic and psychrophilic bacteria count, and extension of the quality of salmon slices to 6 days at 2 ºC.	[117]
Chitosan/nisin, potassium sorbate/silver substituted zeolite	LDPE film incorporated with antimicrobial agents	Total mesophilic aerobic bacteria	Chicken drumsticks	Reduction in the counts of microbes and delayed production of TBARS	[118]
Enzymes and bacteriocins					
Lysozyme	Whey protein isolate-based film	L. monocytogenes	Smoked salmon	Prolonged shelf-life and inhibition of bacterial development	[100]
Lactoferrin, lysozyme	Lactoferrin and lysozyme incorporated paper sheets	Total mesophilic aerobic bacteria	Ready-to-eat thin-cut veal meat	Inhibition of microbial development	[119]
Antimicrobial agent	Packaging application	Microorganisms tested	Food application	Significance	Reference
Nisin/ lacticin	Polyamide and bacteriocin coating on LDPE	Total mesophilic aerobic bacteria, coliforms	Ground beef, fresh oysters	Prolonged shelf-life, inhibition of bacterial growth	[120]
Natamycin	Natamycin incorporated cellulose polymeric and laminated films	P. roqueforti	Gorgonzola cheese	Prevention of fungal growth and product preservation	[121]
Organic acids, their derivatives and other organic compounds					
Acetic acid, rosemary extract and Asian EO	Methyl cellulose	E. coli, Salmonella typhimurium, Listeria monocytogenes	Fresh broccoli	Better efficiency against E. coli, S. typhimurium, and L. monocytogenes with a considerable decrease in bacterial counts to 100% suppression after 12 days of storage	[122]
Citric acid	LLDPE/cornstarch film	Total bacteria	Minced beef	Decrease in bacterial development in comparison to control samples after 10 days	[123]
Potassium sorbate,	Alginate/$CaCl_2$ (EC)	Pseudomonas sp.,	Mozzarella	Decreased growth rate of	[124]

calcium lactate, sodium benzoate, calcium ascorbate		Enterobacteriaceae.		Pseudomonas sp. and Enterobacteriaceae in 3% potassium sorbate incorporations	
Nano particles					
Ag/TiO_2	Polyethylene	Molds, yeasts, B. cereus, B. subtilis	Bread	Extension of shelf-life for up to 6-day storage period	[125]
Ag/ZnO	LDPE	E. coli, L. monocytogenes, and P. aeruginosa	Chicken breast fillets	Decrease in microbiological development	[126]

C. Regulating or buffering

Humidity control/ moisture absorption - Water activity and moisture content are two key elements influencing the storage quality of many foods. High humidity levels inside the packaging encourage the development of spoilage microbes, soften dry and crispy food items like nuts, pasta, crackers, and biscuits, induce hardening and particle aggregation in freeze-dried instant coffee or milk powder, and moisten hygroscopic products like candies and sweets [33], all of which result in quality losses and shorter shelf life, resulting in low consumer appeal. Conversely, high moisture loss across the packaging may cause desiccation of the packaged food components or this may accelerate fat oxidation [60]. Therefore, it is critical to strategically design packaging to control moisture in packaged foods in order to avoid moisture-related deterioration by regulating the migration of macromolecular food moisture, desorption of high moisture foods, or adsorption of dry products within the tolerable moisture range.

To avoid these undesired consequences and maintain the proper relative humidity in the package headspace, moisture-controlling sachets, pads, desiccants (absorbers), or films with appropriate water vapor permeability have been developed. The mechanism of action is dependent on a process of absorption [33], [127]. Desiccants including montmorillonite, bentonite clays, or silica gels, calcium sulfate or calcium oxide, molecular sieves, cellulose fibers, polypropylene glycol, polyacrylate salts, carbohydrates, and minerals, purge pads, humidity controllers with high hygroscopic and dehydrating ability are being used [18]. Trends in moisture-scavenging food packaging systems are listed in Table V. Desiccants come in the form of customized designs such as canisters, tablets, closures, disks or inserts, or sachets, and are intended to be used in combination with highly moisture-resistant packing materials. They could be integrated into polymer-based structures for use as foil and barrier laminates such as oriented polypropylene (OPP), hot melt tapes, and metalized polyester to be formed into foil blisters (Activ-Blister®, CSP Technologies, Inc.) and pouches (SuperDryFoilTM, Baltimore Innovations Ltd.) [18].

Table V. Trends In The Application Of Moisture-Scavengers In Food Packaging

Active substance	Packaging	Food application	Significance	Reference
NaCl	Spun bonded polyethylene pouches	Tomatoes	The shelf life of packed red-ripe tomato fruit was prolonged from 5 to 15-17 days when stored at 20 °C by the delay of surface mold development	[128]
NaCl	Thermoformed multilayer trays: PE/ NaCl/PE	Strawberries, tomatoes	Maintaining the package's RH below 97% for 7 days at various storage temperatures	[127]
Bentonite/sorbitol/calcium chloride	Powder in pouches/ trays within the package	Mushrooms	Reduced moisture condensation and enhanced physical appearance; reduced oxidation discolorations; prolonged shelf-life from 1-3 to 5 days at 10 °C	[129]
A cross-linked poly (acrylic acid) sodium salt powder	Porous “tea bag” membrane integrated into sealed containers	Maize	Used in grain drying to achieve a reduction in mold development (up to 4 ng/g, at 20, 30, and 40 °C drying conditions)	[130]

Specialized drip-absorbent sheets, which are marketed as Cryovacs®, Fresh-R-Pax® (Maxwell Chase Technologies), Dri-Loc® (Sealed Air Corporation), and MoistCatc™ (Kyodo Printing Co., Ltd.), could be developed to eliminate drip loss seeping from muscle-based foods and fresh-cut commodities [102], [131]. Humidity controllers are used in a range of food commodities such as cheese, meat, spices, nuts, and cakes to maintain the ideal package relative humidity, delay moisture loss, and decrease residual moisture in package headspace [128]. Breathable films/membranes (Pebax®, Arkema) and microperforated film (Xtend®, StePac L.A. Ltd.) can be developed to provide high water vapor permeability for fresh foods, reducing the problems associated with excess moisture [15]. Nor®Absorbit (Nordenia International AG) film is a moisture-absorbing microwavable flexible packaging material that absorbs water and excess oil emitted by packaged food during microwave cooking while preserving crispiness [9].

B. Commercial applications of active food packaging

Table VI. Commercial Applications Of Active Food Packaging Systems

Type	Commercial name	Materials and forms	Function	Application	Reference
Oxygen scavenger	Ageless®, ATCO®, FreshMax®, StabilOx®, FreshPax®, BestKept, Keplon®, Wonderkeep®, Everfresh®, Oxy-Guard™, Bioka, O2O™	Iron/sachets or labels	Inhibition/retardation of microbial growth and activities, reduction of rancidity or off-flavor, color changes, and insect infestation.	Bakery, cheese, coffee, seafood, cured meat, snack foods, nuts, spices	[29], [21]
	Tamotsu®, Wonderkeep™ type K	Catechol/sachet	Inhibition/retardation of microbial growth and activities, reduction of rancidity or off-flavor, color changes, and insect infestation.	Beverages	[89]
	ZERO$_2$®	Photosensitive organic dyes/ polymeric matrix, e.g., bottles, films, closures, trays	Retardation of nutritional loss, flavor, and changes in color	Beverages	[89]
	OxyCatch™, OmniBatch®, OmniKeep®	Cerium oxide/ polymeric films	Minimizing the oxidation of active ingredients	Pharmaceuticals	[24]
	Oxyguard®, Ageless OMAC®	Iron/polymeric matrix, e.g., films, trays, bottles, liners, closures	Inhibition of rancidity, changes in color, and the development of off-flavor	Retort food	[89]
Carbon dioxide scavenger	CRISPER NK	Sachet	Preservation of freshness	Fresh fruits	[15]
	TaePoongGel, EVER FRESH®	Sachet	Development of volume and internal pressure	Kimchi	
Type	Commercial name	Materials and forms	Function	Application	Reference
Ethylene control	EVER FRESH® type ETS, Ethylene Control™, Ethyl Stopper™, BeFresh™, GreenPack	Potassium permanganate -based ethylene scavenger	Reduction of the freshness loss due to senescence, ripening, and postharvest disorders occurred by ethylene	Fresh fruits and vegetables	[33]
	Evert Fresh®, Green Bags™, Peakfresh®, BioFresh®	Mineral powders incorporated PE film			
Moisture control	MiniPax®, Sorb-it®, DesiMaxSLF, SuperDryFoil™, Activ-Blister®, Formpack®	Desiccants: molecular sieves, clay, silica gel, calcium sulfate/calcium oxide sachets	Inhibition of microbial growth and activities, and texture, flavor, and nutrient loss, etc., and oxidation of active compounds	Dry food products e.g., cereals, grains, peanuts	[16]
	Cryovacs®, Dri-Locs®, SupaSorb®, UltraZap®, Luquasorb®, Toppan Sheet®, Fresh-R-Pax	Purge absorbents or polymeric packaging such as lids, films	Inhibition of microbial development and metabolism, ensure moisture is locked in	Ready-to eat-meat, minimally processed fresh produce	
	Tyrek®	Heat-sealed salt in spun-bonded polyolefin film sachets	Inhibition of microbial development and metabolism, prevention of textural changes	Fresh fruits and vegetables	
Dual function	Agelesss® type E	CO_2 scavenger + O_2 scavenger	Control changes and losses in flavors	Coffee	[53], [132]
	Negamold®	Ethanol emitter + O_2 scavenger	Inhibition of microorganism growth and activities	Baked and intermediate moisture foods	
	CO_2 Fresh-Pads, UltraZap® XtendaPak	Purge absorber + CO_2 generator	Inhibition of microbial development and metabolism	Minimally processed vegetables and fruits, and ready-to-eat meat products	
Anti-microbial control	Microsphere®, Microgarde®	Chlorine dioxide generating sachets/ films	Inhibition of microbial development and metabolism	Cooked meat and poultry, cured meats	[21]
	Agion®, Apacider®, Bactiblock®, Nanograde®, Bactekiller®, Irgaguard®,	Metallic-based micro and nano-structured materials	Inhibition of microorganism growth and activities	Fresh fruits and vegetables, bakery products, meat and poultry, cheese	

	Surfacine®, IonPure®				
Flavor/ emitters and absorbers	Anico™, Compel Aroma®, BMH™, Aroma-Can®	Film	Odor stabilization	Fried snack foods, fruit juices, cereals, dairy products, fish, poultry	[21]
Odor absorbers	MINIPAX®, STRIPPAX®	Sachet	Odor absorption caused by the formation of H_2S and mercaptans in packaged foods during distribution	Peanuts and cereal products	[16]

IV. INTELLIGENT PACKAGING

The food quality and functionality of packaged foods may vary after they have been packaged due to the condition of the packaged food and the effects of external circumstances. Therefore, food safety and quality must be constantly monitored throughout the supply chain [10], [133]. Intelligent packaging, one of the emerging smart food packaging solutions, employs efficient, simple, and precise technologies. This offers an effective intelligent function in comparison to traditional packaging approaches by conveying information to consumers based on the ability to sense, identify, or track internal or external changes in the food. Intelligent packaging is "materials and items that control the state of packed food or the environment that surrounds the food," according to the European Food Safety Authority [19].

A. *Categories of intelligent food packaging systems*

Intelligent packaging systems make use of three main technologies. They are indicators, sensors, and data carriers [133].

- Food quality indicator systems: Indicators are used to track the quality aspects of the food by making it more convenient for consumers and/or notifying them about the quality of the food. e.g., temperature indicators, gas indicators, and freshness indicators.
- Environmental conditions: These provide for the precise identification of analytes in foods and the monitoring of situations that may cause changes in the food quality attributes. e.g., relative humidity sensors, gas leakage sensors.
- Data carriers: These devices are designed particularly for storing, distributing, and tracking information. e.g., bar codes, radio frequency identification systems [133]

1) *Food quality indicators*

Indicators are different from sensors in that they do not contain a specialized transducer or receptor; instead, they simply convey information on the availability or concentration of a specific drug, or the intensity of a reaction between two or more analytes via rapid visual changes [21], [134]. All the food quality indicators may be classified into three groups: temperature indicators, freshness indicators, and gas indicators [29].

Temperature indicators - Temperature indicators (TI) operate depending on the temperature variations in the food or the package comprising the product, indicating any deviation in product critical temperature and alerting consumers on the risk of microbial activity and protein denaturation during freezing or defrosting. They are divided into two groups: simple temperature indicators, and time-temperature indicators (TTI) [2]. The most prominent TI for indicating that food is at the proper serving temperature after microwave heating or refrigeration is the thermochromic ink dot, which is primarily used for beverages or microwavable foods [4].

Time-temperature indicators - Time-temperature indicators are economical, user-friendly, simple devices included in the package that provide information concerning temperature abuse, especially for frozen or chilled foods. Based on their functionality, TTIs may be divided into three groups. The critical temperature indicator indicates if foods have been overheated or chilled below a set temperature. The partial history indication reflects whether a commodity has already been treated to temperatures strong enough to induce a modification in the food quality, while the full history indicator reports the continuous temperature profile throughout the food supply chain [133]. TTI's basic operating concept is regarded as identifying irreversible responses of time and temperature-dependent chemical, mechanical, electrochemical, microbial, or enzymatic modifications in a food product at elevated temperatures [269]. Physical or chemical responses based primarily on acid-base interactions, as well as biological responses with regard to time and temperature, are generally described as “visible responses” [135]. They are typically small self-adhesive tags or labels that are inserted into or applied to packaging.

Un et al. [136] developed an isopropyl palmitate (IPP) diffusion-based TTI which was designed to assess the microbial safety of unpasteurized angelica juice. It was found that the diffusion of IPP up to 7.0 mm was the point of the threshold to determine the microbial spoilage and juice quality. A lactic acid-based TTI was designed for evaluating the quality of vegetables, fruits, and other oxygen-sensitive foods, and it was regarded as a promising tool for detecting food quality deterioration [137]. Some examples of recently developed TTIs are listed in Table VII.

TTIs that are commercially accessible function in enzymatic, microbiological, diffusion, photochemical, polymer-based, and barcode technologies. The commercially available TTIs function on enzymatic, microbiological, diffusion, photochemical, polymer-based, and barcode systems. Some of the TTIs that are already on the market include 3M CheckPoint®, MonitorMark™, Coolvu™, OnVu™, Fresh-Check®, TopCryo™, Timestrip®, ThermRF Logger, WarmMark®, and VarioSens® Time-Temp Tags, among others. Keep-it® is a chemical reaction-based TTI developed by Keep-it technologies, Norway, that comprises a mobile reagent ferrocyanide and an immobilized Fe^{3+} that is activated once the seal is removed, resulting in a visual colorimetric response [57]. OnVu™ (Ciba Specialty Chemicals, Inc., Switzerland) is an irreversible indicator [132] that functions by activating a photochemical reaction when exposed to ultraviolet rays, resulting in a color change. The color fades over time when exposed to temperatures greater than the reference temperature [9]. The 3M Monitor mark® (3M Co., USA) is a diffusion-reaction-based device that comprises a blue dye that is combined with a fatty acid ester with a specific melting point. The free fatty acid ester melts and diffuses when exposed to a temperature above its critical temperature, causing the indicator to change color. The company TRACEO is developing a microbiological reaction-based TTI called Topcryo™, which consists of 3 layers, and the breakage of these 3 layers may happen due to the exposure to a temperature over its critical temperature, resulting in a color change which is caused by an enzymatic reaction initiated by the bacteria.

Table VII. Examples For Recently Developed Time-Temperature Indicators

Indicator components	Application	Principle and properties	Reference
Dimethyl sulfoxide with RFID	Monitoring of the supply chain	Works based on the melting point of a specific solvent. The micro fluidic-critical temperature indicator ranges between 18–19 °C for fresh-cut fruits and presents a fast response to the critical temperature	[138]
Tributyrate, glycerol, and aspergillus niger lipase	Fish, vegetables, and fruits	A lipase type enzymatic reaction-based TTI prototype was developed based on the interaction between Aspergillus niger lipase and glycerol tributyrate	[139]
Carbamide and urease	Perishable fruits	Works by combining urease with carbamide in a chemical reaction	[140]
Anthocyanin from red cabbage, PVA, and chitosan	Packed foods, e.g., milk	Acts as a natural indicator and can monitor temperature changes indirectly through the product's pH variation, which happened as a result of the product being stored at an improper temperature	[141]
Leuco methylene blue), a mixture of L-cysteine and L-ascorbic acid, O_2	Sandwich	A printed TTI was created that could be held at room temperature until use and simply triggered by air when the vacuum package was opened, and the color changed when exposed to air	[142]

Freshness indicators - A variety of indicators based on intelligent packaging concepts are used to assess food freshness, especially for vegetables, fruits, and their fresh-cuts. Freshness indicators give an immediate indication of product quality changes concerning spoilage or lack of food [16]. Furthermore, they can recognize the chemical ripening index to track the stage of fruit ripening.

Food spoilage indicators - An indicator that particularly reveals food spoilage or loss of freshness, as well as container leakage, temperature abuse, or gas change, might be excellent for the quality management of refrigerated foods. The major indicators of food freshness are metabolites or chemicals such as ethanol, organic acids, glucose, biogenic amines (e.g., cadaverine, tyramine, histamine, putrescine), volatile nitrogen compounds, ATP degradation products, carbon dioxide, sulfuric compounds, aldehydes, ketones, and esters [57], [143]. The presence of at least one of these chemicals or metabolites during food deterioration leads most freshness indicators to change color [131]. A colorimetric chitosan bio-based pH indicator with the capability to be applied as an indicator of metabolites such as L-lactic acid, n-butyrate, and D-lactate generated during microbial development has been developed [144]. A colorimetric array freshness indicator for assessing the freshness of packaged chicken breasts that work on the development of total volatile base nitrogen (TVBN) and CO_2 from the chicken meat as quality indicators was developed [145]. A pH sensor based on polyaniline film has been developed as an on-pack single color indicator for real-time monitoring of microbial breakdown products in packed fish headspace [146]. This indicator shows a noticeable color variation in a range of basic TVBN releases after seafood spoilage.

Table VIII. Recent Developments In The Food Applications Of Freshness Indicators

Indicator components	Application	Significance	Reference
Food spoilage indicator			
pH-sensitive dye (bromocresol green) coated onto PET substrate discs	Fish	Has the ability to produce dynamic expiry dates, which might help with quality assurance	[153]
pH indicators [bromo cresol purple (BCP) and methyl red (MR)]	Beef	The dual-color indicators may identify beef deterioration, with the BCP changing from yellow to purple and MR changing from red to yellow	[146]
Agarose immobilized myoglobin	Unmarinated broiler cuts	Indication of the presence of H_2S by a visible color change of agarose immobilized myoglobin	[154]

Starch/PVA film incorporated with Hibiscus sabdariffa L. anthocyanins	Silver carp	The presence of TVBN amines caused apparent color variability with time, and the film could be used to examine the fish instantaneously	[155]
Ripeness indicator			
Starch/chitosan incorporated with pH dyes (MR, bromothymol blue)	Fresh-cut durian	Well–suited to detect S-compounds which accounted for 70% of total volatiles and indicator changes its color based on sulfur concentration.	[152]
Bromophenol blue on bacterial cellulose membrane	Guava	The reduction in pH induced by the generation of volatile organic acids led to change color from blue to green, indicating over-ripeness	[156]

Ripeness indicators - Fruit ripening results in a series of biochemical changes such as the production of pigments, loss of chlorophyll, changes in organic acids, conversion of starches into sugars, proteins and fat content, aroma and flavor development, reduction in tannins and fungistatic compounds, and an increase in ethylene production [47], [147]. Color changes can help customers determine whether the fruit is perfectly ripened and ready to eat. However, certain fruits do not have a visible visual indicator of ripening [148]. Indicator systems have been developed to convey qualitative information regarding ripening through visual colorimetric changes due to acidic or basic reactions. In this regard, color–based pH indicators are being used to detect the secondary metabolites of fruits to indicate the fruit ripeness as aromas can trigger pH fluctuations [29]. The pH dyes can be employed to indicate the presence of basic or acidic volatile substances and to exhibit an irreversible change in visual appearance based on color changes [135]. A ripeness indicator under the trade name RediRipe®, targeted ethylene based on the oxidation of ethylene, was developed by the University of Arizona (USA) in 2005 [16]. It is composed of cellulose-based ammonium-molybdate as a visual dye (white) and palladium (II) sulfate, a catalyst where the indicator sticker may react with ethylene to generate molybdenum oxide (MoO_3), gradually changing the color to dark blue [149]. In another study done by Iskandar et al. [148], they developed a ripeness indicator with the composition of ammonium molybdate and hydrogen peroxide and PVA as the base material. In contrast, label application in a pack of avocados showed a higher correlation between fruit quality degradation and label color changes. The world's first intelligent sensor label that indicates fruit ripeness, RipeSense®, was developed by Jenkins Group (Auckland, New Zealand) [150], [151]. The indicator substance, which uses phenol red as a pH dye on an alkalized solid-phase indicator film, may interact with aromatic esters to form carboxylic acids, resulting in a color shift that indicates fruit ripening. Consumers are able to distinguish fruit as juicy, firm, or crispy by correlating the color of the indicator to the extent of ripeness. It has been used effectively on melon, pears, avocado, mango, kiwi fruit, and stone fruits [152].

Gas indicators - Permeation processes across the packing material, microbial metabolism, package leakages, and chemical or enzymatic activities on the food material all contribute to changes in the gas composition within the package [17]. Gas indicators, which are printed on packaging films or available as labels, are capable of reacting to changes in gas composition, detecting leakages, and ensuring the efficacy of CO_2 and O_2 scavengers, aiding in the monitoring of packaged food safety and quality. Most of them are used to check and monitor the O_2 and CO_2 concentrations, as well as water vapor, ethanol, hydrogen sulfide, and other gases [131]. Consumers can track the packaged food quality by analyzing common redox dyes (methylene blue, often used as a leak indicator) on the label, and damage to individual packages can be identified by a quick visual inspection without unwrapping the packaging.

Vu and Won [157] have developed a UV-activated oxygen concentration indicator film consisting of thionine, P25 TiO_2, glycerol, and an encapsulating polymer with zein as a redox dye for the sensing of O_2 gas and the inhibition of colors seeping out from the package. It may quickly return to its initial color with the aid of O_2 gas. A CO_2 indicator that does not interfere with the food packaging material composed of methyl red or bromocresol purple was developed [158]. Also, it helps track food deterioration throughout the supply chain. Furthermore, gas indicators can be combined with RFID tags to allow for distant monitoring [17].

2) *Sensors* - A sensor is a device that detects, locates, or quantifies energy or matter by generating a signal in order to detect or measure a physical or chemical attribute [159]. A sensor has four main components: the receptor (or sensing section), the transduction element, the signal processing unit, and the display unit. The receptor primarily converts the physicochemical signal into a kind of energy, and the transducer converts that energy into a meaningful analytical signal that can be measured by external equipment [2]. In terms of food packaging applications, sensors are classified into three categories according to the type of receptor: chemical sensors, biosensors, and gas sensors.

Chemical sensors - A chemical sensor is an analytical device that employs a chemical reagent as a receptor and can determine the availability, composition, concentration, or activity of certain gases or chemical analytes by surface adsorption by inducing a modification in surface characteristics [160]. Then, the transducer detects the presence of certain chemicals and transforms it into a quantifiable signal proportionate to the analyte of interest. Chemical sensors are commonly used to detect changes in pH and volatile organic compounds (VOCs) such as dimethylamine, trimethylamine, and other gases (CO_2, H_2S, H_2, NO_2, CH_4,

NH_3, etc.) generated during distribution and storage inside the package [3]. It is possible to measure ion concentration by measuring the volumetric shrinkage of functionalized hydrogels driven on by the chelation of ingested metal ions [161]. Hydrogels containing conductive polymers, such as poly(3,4-ethylenedioxythiophene) doped with polystyrenesulfonate, exhibit fluctuations in electrical current as a result of pH-dependent swelling or deswelling in the food material [161]. Polyethylene glycol diacrylate hydrogels can effectively use optical waveguides to detect toxic heavy-metal ions like Hg^{2+}. It is possible to produce a smooth surface from the material with little light scattering at the surfaces by the fluorescence of embedded carbon dots which allows for the identification of the metal ions that have been absorbed [161]. Carbon nanomaterials like nanoparticles, graphene, graphite, nanotubes, and nanofibers are applied in chemical sensors to detect pathogenic organisms, spoilage, and chemical contaminants, alterations, and track ingredients or products throughout the production process due to their better mechanical and electrical properties [4]. The multiwall carbon nanotubes/gelatin–polyvinyl alcohol nanocomposites is very promising for application in biosensors leading the nanocomposite to ideal electrode material that can detect interactions between bio-molecules in real time, optical and solid-state gas sensors [162]. Solid-state polyaniline/polyamide nanofiber sensor was developed based on the reversible non-redox acid/base doping process [163]. Even at low concentrations of up to 50 ppb, the film was able to detect L-ascorbic acid and display a noticeable change in color, which could be checked out automatically using an iPhone [163]. A photochemical CO_2 sensor containing a colorimetric pH indicator α-naphtholphthalein and Pt-porphyrin dye encased in a plastic shield could sustain its CO_2 sensitivity for nearly three weeks at 4 °C [164].

Biosensors for bacteria detection - Biosensors are compact analytical devices or tools that detect, record, and transmit information about biochemical reactions [17]. The receptor in a biosensor is an immobilized sensitive element from the biological components (enzyme, hormone, nucleic acid, DNA, and antibodies) that recognizes the target analyte (antigen, complementary DNA, enzyme-substrate or inhibitor, etc.), and the transducer converts biochemical signals into quantifiable electronic responses [17]. Using a polyacrylamide hydrogel packed with mucin (protein) and lithium chloride ions, the system of an artificial tongue demonstrated the potential for detecting polyphenols [161]. An electrochemical biosensor produced from a nylon nanofibrous membrane was used in conjunction with the glucose oxidase enzyme to detect glucose levels in a variety of beverages, including energy drinks, digested milk, coke, and honey [165]. In another biosensor, where xanthine oxide is immobilized on the electrodes composed of silver, platinum, or graphite electrodes, it had the capability to detect xanthine, which is a degradation product of adenine nucleotide in animal tissues [21]. The Food Sentinel System® (SIRA Technologies Inc., USA) is a barcode-based biosensor designed to sense pathogenic microbes in food [17]. The pathogens cause a dark bar to appear in the barcode, rendering it unreadable [54]. Pathogens including *Salmonella* sp., *E. coli* sp., *Campylobacter* sp., and *Listeria* sp. can be detected using ToxinGuard® (Toxin Alert, Canada), a functional model based on antibodies (immunoglobulin) that are incorporated into plastic packaging [166].

Gas sensors - The gas concentration within food packaging gives indirect information on food quality since it might fluctuate over temperature and/or time due to chemical, biological, or physical processes or leakages [167]. Gas sensors can distinguish and confirm the availability of volatile or gaseous analytes such as volatile amines, CO_2, O_2, and other particular gases inside the package headspace. They comprise amperometric oxygen sensors, potentiometric carbon dioxide sensors, ethanol sensors, water vapor sensors, piezoelectric crystal sensors, organic conducting polymers, metal oxide semiconductor field-effect transistors, etc. [29]. Optical oxygen sensors relying on absorbance changes or luminescence quenching caused by direct contact with the target analyte have been designed. They are used to detect gases that affect food quality, such as carbon dioxide, hydrogen sulfide, and volatile amines that affect food quality [164]. Furthermore, gas sensors can be employed with pH-sensitive dyes for detecting basic volatile amines in protein-rich foods [168]. CARBOTEC TR-PT© (Centec Co.) is a commercial CO_2 sensor developed to detect CO_2 in carbonated drinks and dairy products [169]. OxySense in Delaware, USA, produced the O2xyDot, a fluorescence-based oxygen sensor that is installed within the primary packaging prior to filling and can be checked non-destructively from outside the package [170].

3) Data carriers - Data carriers improve the efficiency of information transfer throughout the food supply chain and, as a result, indirectly aid in food safety quality and monitoring. They guarantee traceability, automation, theft protection, or counterfeit protection [171]. The most commonly used data carrier devices in industrial food packaging applications are barcode labels and radio frequency identification (RFID) tags [17].

- Bar codes - A barcode is a visible, machine-readable symbol used to represent data [172] for managing inventory, stock reordering, and price checking [173]. Information regarding food packing date, expiry date, package weight, batch number, cooking instructions, nutritional information, and the website address of the producer can be encoded in the barcodes and they can be read by specialized scanners [131]. In general, barcodes are classified into one-dimensional (1-D) or two-dimensional (2-D) forms [17].

A 1-D barcode is a basic linear pattern of alternately positioned black and white bars, and this is used to store data and information. The fundamental concept is similar to a laser beam cutting a horizontal slice from vertical code bars. Then the beam records the amount of time it takes to scan dark lines and bright regions as it goes over the symbol (Figure 4) and decodes the data into specific information [2].

Fig. 4 One-dimensional bar code [174]

Fig. 5 Two-dimensional QR bar code [175]

Instead of bars and spaces, 2-D barcodes combine spaces, dots, alphanumeric, and numeric data in an array or matrix to contain much more data in far less space than 1-D barcodes (Figure 5) [4]. They can be printed directly on the packaging or affixed to packaging as stickers, providing consumers with further information on the product or a link to a web page with more information [176]. There are several standardized 2-D barcodes used in the food industry, for example DataMatrix, QR Code, Nex Code, Aztec Code, etc. [174].

- Radio frequency identification systems (RFID) - The RFID tag seems to be the most extensive data carrier device for product identification, with many distinguishing features, including considerably high data storage capability, non-contact, non-line-of-sight data collection capability, and data that can enter non-metallic materials for quick and instantaneous diverse product identification [177]. The tags consist of three major components. These include a tag comprised of a microchip connected to an antenna, a reader responsible for emitting radio signals and receiving responses from the tag, and a web server that links the RFID hardware and corporate applications [178]. RFID tags are divided into two types: passive and active, which are distinguished by their battery requirement [179]. The passive tags have no battery, whereas the active tags use the battery as a power source [175]. They offer a wide range of advantages in the food packaging industry, including product identity and traceability, livestock management, cold chain monitoring, shelf-life prediction, and anti-theft or counterfeit protection [2], [175]. Freshtime™ semiactive RFID tags have been developed by Infratab Inc. (Oxnard, Calif., USA) to monitor the storability of foodstuffs by temperature sensing and integrating them over time to compute the shelf life of the product, which may then be conveyed to a reader [180]. Identec Solutions (Lustenau, Austria) offers an RFID-based temperature data recorder (i-Q32T) that may be used to track and document the interior food temperature during production and cool-down periods [181]. Furthermore, RFID devices may be employed to verify that commodities such as meat, fish, vegetables and fruits, and milk products are transported and stored at safe temperature ranges [178]. Turbotag™ is a temperature-monitoring RFID tag from Sealed Air (Elmwood Park, N.J., USA) that may act as a temperature data logger and collect and communicate the temperature history of any commodity that is attached to [178]. The RFID system combined with sensors was developed by the Auburn University Detection and Food Safety (AUDFS) project for detecting pathogenic microbes in food [182]. The project objective was to encapsulate microscopic structures with pathogen-binding viruses or bacteriophages and send a signal to a portable RFID reader when a pathogen interacts with the encapsulated material.

B. Commercial Applications of Intelligent Packaging

Table IX. Commercial Applications of Intelligent Food Packaging Systems

Type	Commercial name	Function	Application	Reference
Time-temperature indicators	Checkpoint®	Cause a color change from green to bright yellow due to the acid production by enzymatic hydrolysis, which leads to a change in pH	Meat, fish, poultry, ground beef products, and dairy products	[175]
	(eO)®	When a product deteriorates or is exposed to extreme temperatures, TTI bacteria exhibit temperature-dependent growth, resulting in a pH reduction and an irreversible color change to red	Spiced, cooked chicken slices and ground beef in MAP	[179]
	Timestrips®	Monitoring the elapsed time on perishable products	Perishable, refrigerated, and frozen products	[172]
	Insignia Deli Intelligent Labels™	Monitoring the freshness with a better indication of time and temperature	Chilled foods	[4], [183]
Freshness indicator	Toxinguard®	Enable the detection of pathogenic bacteria (Salmonella, Escherichia coli O157, and Listeria) using immobilized lactic antibodies.	Meat and muscle-based products	[21]
	FreshTag®	Interact with volatile amines generated during fish storage	Seafood	[29]
	Sensor Q®	Sensing bacterial development within the package	Fresh meat and poultry products	[21]
Gas indicator	ShelfLife Guard®	Identification of the presence of air within the package headspace by changing the color from transparent to blue	Products containing poultry or fish which are stored in modified atmospheres or vacuum packages	[1]

	Ageless Eye™	Indicate the presence of oxygen gas by changing color from pink to blue or purple	Packaged fish, meat products, dairy products	[179]
Gas sensors	OxySense® O_2xyDot™	Quantification of the headspace or dissolved oxygen in transparent or semi-transparent, sealed packages.	Perishable foods and beverages packed under a modified atmosphere	[29]
	Oxy 510 Inline Oxygen Sensor©	Offer reliable and precise monitoring of dissolved oxygen for a broad range of concentrations	Milk, beverages	[169]
	CARBOTEC TR-PT©	Determination of CO_2 content	Carbonated drinks and dairy products	[169]
Type	Commercial name	Function	Application	Reference
Bio sensors	LactoSens®	Assessing the low contents of lactose in lactose-free dairy products	Lactose-free milk and dairy products	[169]
	Toxinguard®	Use immobilized lactic antibodies to identify pathogenic bacteria (Salmonella, Campylobacter sp., and E. coli O157)	Meat and muscle-based products	[21]
Radio frequency identification systems	VarioSens®	Act as a temperature data logger and a tracking tool within the supply-chain	Meat, fish, bakery products, dairy, and beverages	[16]
	WaveSafe™	Eliminate the risk of fire while providing high-accuracy read rates and item tracking	Chilled and frozen packaged foods	[182]
	ThermAssureRF™	Tracking and tracing with temperature measurement, provides a method for processors to comply with Hazard Analysis and Critical Control Point (HACCP) regulations, and trace items along the supply chain	Wine, seafood, meat, poultry	[182]

V. CONTRIBUTION OF NANOTECHNOLOGY FOR FOOD SAFETY MONITORING THROUGH SMART PACKAGING

According to Fuertes et al. [150], nanotechnology could be effective in smart food packaging by incorporating nanomaterials, nanoparticles, and nanosensors into packaging materials, which may include nanofibers, nanotubes, nanosheets, and nanocylinders. Because of the wide range of improved functional qualities that nanomaterials may offer to packages, nanotechnology has become a strong tool for the development of active and intelligent packaging systems. Nanoparticles can be used in smart packaging as reactive particles in packaging materials to convey the state of the packed product [184]. In order to improve product protection and functionality, nanomaterials are used in active packaging development to directly interact with food or the environment. Antimicrobial properties can be provided with silver nanoparticles, silver coatings, nano titanium dioxide, nano magnesium oxide, nano copper oxide, and carbon nanotubes, which can be combined with antimicrobial packaging and oxygen scavengers [185]. Bio-nano composite polymer structures reinforced with nanofiller materials such as clay nanoplatelets, silica nanoparticles, graphene, starch nanocrystals, cellulose nanofibers, metal oxide nanoparticles, and chitin or chitosan nanoparticles are used in smart packaging with nanosensors [169]. The trends in the development of polymeric nanomaterials for smart food packaging and their examples are listed in Table 10.

Table X. Trends In Nanotechnology-Based Smart Packaging Systems

Type	Nano material	Function	Applications	References
Active packaging				
Anti-microbial packaging	Silver nanoparticles	Prevention of microbial development effectively and enhancement of shelf life	Fruits and vegetables as a film	[186]
	TiO_2 nanoparticles	Reduction of E. coli contamination on food surfaces	Fresh cut vegetables and fruits as a film	[187]
	Nisin	Effective antimicrobial activity against gram-positive bacteria	Fish, meat, fruits, vegetables	[188]
	Silver-copper nanoparticles	High antimicrobial properties against Salmonella, Campylobacter, and L. monocytogenes	Chicken meat as a film	[189]
	ZnO nanoparticles	Antimicrobial activity against L. monocytogenes	Fresh-cut mushroom	[190]
Oxygen scavenging film	TiO_2 nanoparticles	Significant lipid oxidation inhibition and off-flavor avoidance	Oxygen-sensitive food products	[191]
Ethylene scavengers	ZnO nanoparticles	Slowdown the rate of fruit decay and ethylene synthesis, better	Fresh-cut apples as a film	[192]

		maintenance of TSS and TA, and suppression of enzyme activity		
	Nano-Ag, nano-TiO_2 and montmorillonite	Inhibition of ethylene production and physiological changes, slowdown the ripening rate	Kiwifruits as a film	[193]
Moisture absorbers	Silver nanoparticles	Effective shelf-life extension of tuna snacks	Snacks, biscuits, crackers as a paper	[194]
Type	Nano material	Function	Applications	References
Intelligent packaging				
Nanosensor	Antibody modified graphene	Detection of a variety of substances, including the allergen- lactoglobulin protein	Milk and dairy products as a film	[195]
	Gold nanoparticles	Detection of melamine in raw milk and infant formula	Milk and dairy products	[196]
	Fluorescent nanoparticles	Detection of pathogens and toxins	Any type of food	[197]
	ZnO nanoparticles	Detection of temperature changes	Any type of food	[198]
Freshness indicators	Nanofibre of polyaniline	Indication of fish freshness	Fresh fish as a film	[6]
O_2 indicators	Nanocrystalline SnO_2	Ensure that no O_2 is present in O_2-free food packaging matrices	Vacuum packed foods	[199]

VI. FUTURE PERSPECTIVES AND CONCLUDING REMARKS

Different smart packaging technologies, including active and intelligent packaging, have already been investigated intensively and commercialized. Currently, they are being applied efficiently in food packaging to enhance quality and safety, as well as consumer convenience and delivery capabilities. The advancement of active packaging enhances the shelf-life stability of the foods, whereas freshness indicators, gas concentration indicators, time-temperature indicators, etc., monitor and preserve the food quality throughout the production process and storage to end-consumers. Moreover, RFID tags, bar codes, and thermochromic inks help secure food products against counterfeiting and theft.

However, studies focusing on the integration of diverse smart packaging techniques into packaging with active and intelligent capabilities offered at the same time are rarely present. Thus, efforts must be made to integrate active and intelligent packaging into a single device capable of giving real-time information about the quality of food products.

Because of their perishability and added value, fruits and vegetables have received less attention than fish and meat in developing smart packaging solutions. However, a similar percentage of food wastage can be observed in other high-value goods such as dairy products, cereals, oilseeds, roots, tubers, and pulses [200]. As these products have not yet been studied concerning smart packaging, researchers will have a chance in the next few years to explore this field.

The development of smart packaging is crucial not just for improving food supply chain management but also for reducing food wastage and environmental pollution worldwide. However, so far, intelligent devices such as optical and colorimetric tags, as well as RFID, sensors, and indicators, have not been developed with biodegradability, recyclability, and/or sustainability mechanisms. Hence, it is possible to establish the potential of effectively employing smart packaging systems based on naturally occurring, biodegradable polymers and plant extracts, such as chitosan, cellulose, and alginates, that may represent innovative solutions for the low-cost, sustainable, and safe production of environmentally friendly intelligent packaging. Furthermore, research can be conducted to ensure that the films do not become hazardous as a result of deterioration once exposed to the natural environment. Bioactive chemicals can be derived from biodegradable food wastes generated from various processing firms and inedible components of plants, which can then be used to develop real-time indicators.

Smart packaging in the form of pouches or sachets has the potential to incorporate additional migratory substances and cause interactions among active ingredients and certain other packing materials [23], [201]. Therefore, greater attention should be paid to health and safety considerations, which present many problems in the development of large-scale packaging. One of the key problems to be fixed before the large-scale application of smart packaging in the future is the development and validation of standardized testing for safety.

Several research gaps must be addressed to solve the current disparity between the possibility and awareness of active and intelligent packaging approaches. There is a huge challenge in finding specific and sensitive quality indicators. This characteristic is lacking in the majority of recent pH-based indicators. Therefore, further research has to be done to find ways to improve their specificity and sensitivity.

Nanotechnology can be integrated further into smart packaging technologies to enhance traceability and management of food conditions throughout storage and transportation, as nanomaterials provide major gains in sensitivity, selectivity, and speed compared to approaches that rely on macroscale materials [172]. Carbon nanotubes, nanosilver, nano copper oxide, nano magnesium oxide, and nanotitanium dioxide are all expected to be used in antimicrobial food packaging in the near future [185]. The distinct properties of nanomaterials can be utilized as a trend in the future for the development of a new generation of electronic devices, such as nano transistors to build future nano processors and nano memory, nanobattery, and nanosensors for monitoring food safety [202].

Nevertheless, due to their high cost relative to conventional packaging and their restricted ability to integrate into current packaging, such methods are still rarely used [134]. Hence, a comprehensive approach is required in designing smart packaging devices that are compact, more sophisticated, and inexpensive for food applications. More advanced intelligent package structures, such as biosensors, are still in the early stages of development, and they are limited in use due to their shorter shelf-life. So far, there are possibilities that exist by combining biotechnology and nanotechnology, and they can be implemented in the future to develop biosensors commercially on a large scale by overcoming the limitations.

Furthermore, steps have to be taken to promote this novel technology. Consumers have to be well informed with greater confidence in the safety of the systems. Finally, the packaging industry also needs to recognize that smart packaging can provide a significant competitive advantage. If all of these requirements are fulfilled, smart packaging technologies for real-time food safety and quality monitoring could be widely adopted in the next few years.

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