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The future of food packaging: A review of active packaging and its applications in food industry

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Abstract

The increasing demand for safe, high-quality, and longer-lasting food products has accelerated the development of advanced packaging technologies in the food sector. Active packaging has emerged as an innovative approach that interacts with the packaged food or its surrounding environment to improve product safety, maintain quality, and extend shelf life. This review provides an overview of the principles, design strategies, and functional mechanisms associated with active packaging systems. Key components such as oxygen scavengers, carbon dioxide emitters, ethylene absorbers, moisture regulators, and antimicrobial agents are discussed in relation to their roles in preserving food freshness and minimizing spoilage. The review also highlights recent developments and practical applications of these technologies in the packaging of various food products, including fruits, vegetables, meat, and bakery items. In addition, regulatory considerations and consumer acceptance related to active packaging materials are briefly examined. Although active packaging offers several advantages, challenges such as regulatory restrictions, cost factors, and large-scale industrial implementation remain significant. Future research directions focusing on sustainable materials and environmentally friendly solutions are also addressed. Overall, this review summarizes current knowledge on active packaging and emphasizes its potential to enhance food preservation and reduce food losses in modern food systems.

Keywords: Shelf-life extension, spoilage prevention, gas control systems, antimicrobial materials, food preservation, sustainable materials, post-harvest quality

Introduction

Food packaging serves as a vital safeguard, ensuring the secure containment and protection of edible products from various threats that may arise throughout the manufacturing, storage, and transportation process. The food packaging industry has undergone significant transformations over the past two decades, driven by innovations in materials and technologies. These advancements have not only facilitated the creation of innovative, minimally processed food products but also yielded cost savings and reduced environmental footprints. The fundamental objective of food packaging is to safeguard the integrity of the product by shielding it from environmental stress, contaminants, and degradation factors, thereby maintaining its nutritional value, textural appeal, and overall wholesomeness throughout the entire supply chain.

Active packaging (AP) is a cutting-edge technology that actively interacts with the packed product or its surroundings to improve the performance of packaging systems. According to Janjarasskul & Suppakul (2018) ^[11], Active packaging involves deliberate incorporation of subsidiary components into or onto the packaging material to optimize the functionality of packaging system. In contrast to conventional packaging, which mainly acts as a passive barrier, AP incorporates active ingredients including moisture absorbers, oxygen scavengers, and antibacterial agents to preserve food quality, increase shelf life, and guarantee safety. Intelligent packaging refers to innovative packaging systems that track and monitor the packaged food's condition, providing real-time information about the food's quality throughout storage and transportation.

Currently, the adoption of active and intelligent packaging systems is gaining traction, primarily in Asian countries and USA, although European uptake remains limited. To ensure safety and efficacy, active and intelligent packaging must meet the following conditions:

- 1. Suitability and Efficacy:** Material selection must align with the intended application, ensuring suitability and effectiveness.
- 2. Good Manufacturing Practice:** Manufacturing of active and intelligent materials must be in compliance with good manufacturing practice.
- 3. Labeling and Information:** Clear labeling and provision of information are essential, detailing usage

guidelines, authorized applications, and pertinent specifics, like the identity and quantity of substances released by active components.

- 4. Safety Labeling:** Non-edible parts must be clearly labeled with the words "DO NOT EAT" to prevent consumer confusion. Label information must be visible, understandable and resistant to fading.

Table 1: Examples of active packaging applications in food industry

Emitting/releasing properties	Antioxidants, carbon dioxide, ethylene, flavours, sulphur dioxide, preservatives
Adsorbing/scavenging properties	Carbon dioxide, ethylene, flavours, moisture, oxygen, taints, UV light
Microbial and quality control	Antimicrobial agents like bacteriocins, fungicides, organic acids, UV-treated packaging materials
Temperature control	Insulating materials, self-heating and self-cooling packaging, temperature-sensitive packaging
Removing properties	Catalysing food component removal: cholesterol, lactose

2. Active Packaging

Active packaging materials dynamically interact with the packaged product and its environment, extending shelf life, enhancing safety, and maintaining quality. This innovative technology encompasses two primary categories- integrated systems where functional components are seamlessly integrated into packaging substrates, and inserted systems, which utilize sachets or pads placed within the packaging to achieve desired effects.

As an advanced packaging technique, active packaging intentionally alters and regulates the internal environment within a package, creating a tailored atmosphere that enhances the quality and safety of the enclosed products. This diverse and multifaceted technology offers tailored solutions to various packaging needs, ultimately increasing product shelf life by mitigating factors that compromise food quality.

2.1 Oxygen Scavengers

By encouraging microbial growth and oxidative processes, oxygen (O₂) in food packaging speeds up spoiling and causes discoloration, nutritional loss, and an unpleasant taste and smell. Deterioration may still occur even when O₂ levels may be lowered to 0.5-2% v/v via vacuum packing and modified atmosphere packaging (MAP).

Iron, platinum, palladium, tocopherol, ascorbic acid, enzymes, and microbes constitute the foundation of oxygen scavenging mechanisms. While palladium-based systems catalyse the conversion of oxygen into water in hydrogen settings, attaining high scavenging rates, nano-iron is effective in both hydrous and anhydrous conditions, lowering O₂ levels to 9.45% v/v (Dey & Neogi, 2019) [5]. For example, compared to conventional MAP, a palladium-based oxygen scavenging sheet greatly minimized lipid oxidation in linseed oil by reducing residual O₂ levels to less than 0.01% v/v (Faas *et al.*, 2020) [6].

Ascorbic acid and tocopherol are the two examples of natural scavengers that work well in food packaging, but they cost more since they need to be activated by metals or UV radiation. The disadvantages of enzyme and microorganism-based scavengers include their susceptibility to temperature fluctuations and the possibility of adverse effects on sensory quality from byproducts or unchecked microbial growth (Dey & Neogi, 2019) [5]. Commercially accessible, Ageless™ oxygen scavengers efficiently inhibit the formation of mold in a variety of food items.

2.2 Carbon Dioxide Emitters

According to Hansen *et al.* (2016) [10], carbon dioxide (CO₂) is essential for preserving food's freshness and avoiding

odor-related spoiling. Because of its antibacterial qualities, the food industry is a key beneficiary of this technology, leveraging it to extend product freshness and preserve nutritional value. By changing bacterial enzymes, cell membranes, and cytoplasmic pH, high CO₂ concentrations are especially efficient at inhibiting microbial development in fresh meat, fish, poultry, and non-climacteric fruits (Vilela *et al.*, 2018) [23]. According to Kuswandi (2020) [15], this antimicrobial impact reduces microbial development during the logarithmic phase and lengthens the lag phase.

Hansen *et al.* (2016) [10] showed how CO₂ emitters and MAP can enhance the cod loin's microbiological and sensory qualities. These CO₂-emitting devices, formulated with citric acid and sodium bicarbonate, are triggered by fluctuations in pH levels and moisture from food products, initiating a controlled release of carbon dioxide. In order to maintain quality during storage, the emitters make sure that the CO₂ partial pressure is greater. Furthermore, ferrous carbonate (FeCO₃) emitters are used in active packaging because of their ability to release CO₂ due to their solubility in acidic condition, which supports preservation mechanisms (Vilela *et al.*, 2018) [23]. These systems can be adjusted to meet certain dietary needs.

2.3 Ethylene Scavengers

Ethylene, a plant hormone which significantly impacts the physiological characteristics of fruits and vegetables. By stimulating respiratory processes, it promotes ripening and maturation, ultimately culminating in spoilage and deterioration of fresh produce (Kumar *et al.*, 2022) [14]. Ethylene does not significantly affect non-climacteric fruits like citrus in natural ripening but can be used artificially in some cases. Ethylene causes major quality loss in climacteric fruits (like bananas, mangoes), it causes losses in climacteric fruits due to accumulation, hastening senescence and decay (Kou *et al.*, 2021) [11]. To increase shelf life and to maintain physico-chemical characteristics, excess ethylene must be avoided. Ethylene scavengers, which absorb or scavenge ethylene from the package atmosphere, offer a solution.

Ethylene scavengers employ two primary mechanisms to control ethylene levels:

- 1. Chemical oxidation:** Potassium permanganate is a common oxidizing agent used in ethylene scavengers. It converts ethylene into carbon dioxide and water through oxidation, indicated by a color change from purple to brown. However, due to toxic nature

potassium permanganate, it cannot be used in direct contact with food.

2. **Absorption:** Some materials can absorb ethylene, either independently or in combination with an oxidizing agent.

LDPE and HDPE polyethylene films can absorb ethylene, making them suitable packaging materials for food. These ethylene-absorbing films help maintain freshness and eliminate odors, contributing to extended shelf life and improved food quality (Prasad & Kochhar, 2014) ^[20].

Ethylene scavengers are incorporated into packaging sheets, sachets, and polymer-based nanocomposites using inventive techniques. Ethylene is effectively oxidized by advanced methods that combine titanium dioxide (TiO₂) or palladium with activated carbon under UV radiation. Developing economical, secure packaging solutions still requires addressing issues with material migration, sachet breakage, contamination, expense, and the environment (Gaikwad *et al.*, 2020) ^[9].

2.4 Moisture Absorbers

The food sector relies heavily on humidity, which impacts product quality, safety, and shelf life throughout storage and transportation. Excessive relative humidity (RH) in packaged foods degrades their nutritional value and sensory appeal by accelerating microbial development and spoiling, especially in products with high moisture content, such as meats and fresh produce. Effective solutions that physically absorb moisture or remove liquids that are emitted. Moisture-control solutions are available in various formats, including packets, sheets, absorbent pads, and containers, to suit diverse packaging needs. Moisture removers like pads absorb emitted fluids to prevent spoilage, while RH controls like desiccants maintain low headspace humidity (Yildirim *et al.*, 2018) ^[26].

Organic moisture absorbers including sorbitol, fructose, and cellulose are becoming more and more popular. At 55% RH, cellulose-based films exhibit efficient moisture absorption, whereas fructose, a hygroscopic monosaccharide, absorbs moisture (Maboenchuay *et al.*, 2016) ^[16]. However, inorganic alternatives like calcium chloride and silica gel, which are widely used in industry, are more effective and less expensive than organic absorbers.

Semi-permeable materials are used in the construction of commercial sachets such as Desi Pak and FreshPax® to ensure stability during handling. Additionally, moisture-absorbing trays as UltraFresh System and Fresh-R-Pax® efficiently control humidity. Although they have a lower absorption capacity than sachets, advanced polymeric films containing distributed salts, including NaCl, maintain RH and low water condensation (Sangerlaub *et al.*, 2020) ^[22]. To maximize packing performance, choosing moisture absorbers requires striking a balance between cost, customer acceptability, absorption efficiency, and regulatory compliance. To improve the effectiveness and commercialization of organic absorbers, more research is required.

2.5 Antimicrobial Packaging

The incorporation of antimicrobial agents in food packaging plays a crucial role in inhibiting microbial growth, extending product's shelf life, and enhancing overall food

safety and quality. As the active chemicals are gradually released from the film surface, maintaining the necessary concentration for germ control, research suggests that antimicrobial films can be more effective than direct application in some cases, as they allow for a controlled, sustained release of active compounds, maintaining the necessary concentration for microbial control over time. By doing this, chemicals that might cause loss of function or undesirable interactions with food components including lipids and proteins, are prevented from leaking into the food. It has been proposed that multi-layer films, particularly three-layer systems, can enhance controlled release efficiency. The inner layer regulates the active chemical's spread, the middle layer houses the antimicrobial agents, and the outside layers keep the compound from escaping.

Numerous substances have demonstrated strong antibacterial action, such as silver, zinc oxide, lauramide arginine ethylester (LAE), and essential oils. The efficacy of LAE, a cationic substance derived from natural amino acids, in reducing *Salmonella* and *Listeria* in baby formula packaging has been investigated (Muriel-Galet *et al.*, 2012) ^[18]. Zinc oxide and other metal-based nanoparticles combined with polylactic acid (PLA) have shown excellent antibacterial activity against bacteria such as *Staphylococcus aureus* and *Escherichia coli*; the concentration of the nanoparticles affects their effectiveness (Zhang *et al.*, 2017) ^[27].

Clove, rosemary, and orange peel essential oils have demonstrated the ability to prevent microbial development in food packaging (Maisanaba *et al.*, 2017; Felix de Andrade *et al.*, 2020) ^[17, 7]. However, the organoleptic qualities of food may be adversely affected by their high concentration needs, which calls for more study to create efficient, non-intrusive concentrations (Vilela *et al.*, 2018) ^[23]. Other antibacterial substances with potential for food preservation include chitosan and nisin (Wang *et al.*, 2015) ^[24].

2.6 Ethanol Emitters

Ethanol emitters reduce spoilage and extend shelf life by releasing ethanol vapor into the headspace of food packaging, which inhibits the growth of spoilage causing microorganisms like bacteria, yeast, and mold. Ethanol's antimicrobial properties assist by maintaining the quality of products including mangoes, sliced wheat bread and bayberries. Despite their benefits, conventional ethanol emitters have disadvantages such as uncontrolled volatilization, off-flavors, and consumer reluctance. Ethanol-emitting films and sachets with potent ethanol-barrier properties are used in commercial products such as Oitech™, EthiCap™, and Ageless™ to solve these issues (Bodbodak & Rafice, 2016) ^[1].

Mu *et al.* combined ethanol with sodium stearate and diatomite to create a controlled-release ethanol emitter in order to address the constraints of conventional emitters. The resultant gel turned into a white powder, and by varying the sodium stearate concentrations, the pace at which ethanol was released could be regulated. In Chinese bayberries, these emitters successfully restricted the formation of malondialdehyde, a marker of lipid peroxidation, preserved firmness, and decreased deterioration. To improve this technology for wider applications and environmental conditions, more study is necessary.

2.7 Sulfur Dioxide Emitters

When storing a variety of agricultural items, such as coconuts, walnuts, peppers, tomatoes, and carrots, sulfur dioxide (SO₂) emitters are useful in avoiding discoloration. These emitters work by the reaction of calcium sulfite with moisture or hydrolysis of metabisulfite (Kuswandi, 2020) ^[15]. Malolactic fermentation-causing bacteria, fungi, oxidative degradation, and enzymatic and nonenzymatic browning are all inhibited by sulfites like potassium and sodium metabisulfite. Polyphenol oxidase is also directly inhibited by them.

However, sulfite usage is highly limited due to health hazards including allergic reactions, urticaria (hives), low blood pressure (hypotension), and dermatitis. According to Codex Alimentarius, products containing more than 10 mg/kg or 10 mg/L of sulfites must include allergen labeling (Pisoschi *et al.*, 2020) ^[19]. Despite their effectiveness, there is limited research on the use of sulfites in food preservation because of regulatory and health issues.

2.8 Antioxidant Release

To stop fatty food ingredients from oxidizing, antioxidants are added to polymeric packaging materials or applied as coatings on food surfaces. Butylated hydroxyanisole (BHA), and butylated hydroxytoluene (BHT) are widely employed as synthetic antioxidants, research has highlighted their potential negative impact on human health; the US Department of Health and Human Services has classified BHA as reasonably anticipated to be a human carcinogen (Kuswandi, 2020) ^[15].

Growing concerns over safety and regulatory compliance have led to a shift towards natural antioxidants as substitutes for synthetic antioxidants such as ascorbic acid, essential oils, polyphenols, and retinol (Deshmukh & Gaikwad, 2022) ^[4]. Researchers have developed innovative antioxidant packaging solutions using natural extracts. For instance, Riaz *et al.* (2020) ^[4] created chitosan-based antioxidant packaging infused with Chinese chive root extract, achieving increases in antioxidant activity of 47.05% and 57.38% in DPPH and ABTS assays, respectively. Similarly, Deshmukh *et al.* (2022) ^[4] developed an antioxidant packaging biopolymer using litchi shell extract, halloysite nanotubes, and a natural biopolymer. The resulting film exhibited enhanced physical, mechanical, and barrier properties, with antioxidant activity increasing by over four times compared to the control film.

3. Intelligent Packaging

Intelligent packaging incorporates sensors or indicators that monitor headspace gas composition, temperature, and microbial activity of the food. These innovative systems provide real-time monitoring and feedback, enabling consumers and suppliers to make informed decisions. Key Characteristics of Intelligent Packaging Indicators: Easy activation and measurement; Irreversible, time and temperature dependent changes; Reproducible and correlated with food quality; Provide clear information on package status (Prasad & Kochhar, 2014) ^[20]. By integrating

intelligent packaging solutions, the food industry can enhance food safety, reduce waste, and improve overall quality control.

Types of Intelligent Packaging Technologies

3.1 Time-Temperature Indicators (TTIs)

TTIs are used extensively in the food and pharmaceutical industries to track temperature exposure over time. These indicators irreversibly change color when exposed to temperatures beyond the threshold, indicating potential spoilage. Studies indicate that TTIs can reduce food waste and improve consumer trust in perishable goods (Kuswandi *et al.*, 2011) ^[15].

3.2 Gas and Chemical Sensors

Gas sensors in intelligent packaging detect changes in headspace oxygen (O₂), carbon dioxide (CO₂), and ammonia (NH₃) levels, which serve as indicators of microbial activity or spoilage. These sensors are especially useful in meat, dairy, and seafood packaging where freshness is crucial.

3.3 RFID and QR Codes

Radio-frequency identification (RFID) tags enable real-time tracking of products throughout the supply chain. They help in preventing counterfeiting, ensuring quality control and enhancing inventory management. Additionally, QR codes allow consumers to scan packages using smartphones to access information such as nutritional content, origin, and expiration dates.

3.4 Biosensors

Biosensors detect biological changes such as microbial contamination or toxin presence in food and pharmaceuticals. These sensors often use enzyme-based, antibody-based, or DNA-based detection methods, ensuring consumer safety (Prasad & Kochhar, 2014) ^[20].

Intelligent packaging is revolutionizing the monitoring and management of food products. By integrating sensors, RFID, and digital technologies, it enhances product safety, quality assurance, and consumer engagement. However, high implementation costs and regulatory approval hurdles must be addressed to ensure widespread adoption. As research advances, the packaging industry will likely evolve toward more eco-friendly and integrated intelligent systems. The pioneering iron-based oxygen absorber, Ageless® was introduced to the Japanese market by Mitsubishi Gas Chemical Company in the late 1970s. Today, similar products are manufactured by other companies under various brand names, such as FreshPax® and FreshMax® by Multisorb Technologies Inc. These early absorbers feature zeolites coated with iron (II) oxide and sodium chloride. When exposed to oxygen and moisture from packaged products, the iron (II) oxide oxidizes to iron (III) oxide, effectively scavenging oxygen. Recent advancements have led to the development of more efficient iron-based oxygen scavengers, utilizing metallic iron produced through electrolytic reduction (Kozak, & Cierpiszewski, 2010) ^[3].

Table 2: Summarizes selected active packaging solutions and their potential functions and applications in the food retail industry (Wyrwal & Barska, 2017) ^[25].

Type of packaging	Form	Functions	Applications	Commercial Trade name
Active Packaging				
Oxygen scavengers	Sachets, films, labels, crown caps, pouches, masterbatch	Prevent oxidative rancidity, inhibition of aerobic bacteria, moulds, yeasts growth, reduce enzymatic discoloration	Bread, cakes, biscuits, pizza, pasta, cheese, dried fruits, oils, fats, beverages cooked rice, cured meats, fish, coffee, snack foods, dried beef	ActiTUF™ Ageless® ATCO® Bioka Celox™ Cryovac® OS2000 Enzyme-based FreshMax® FreshPax® OMAC® OxyGuard® OxyCatch® OxyRx® Shelfplus®
Carbon dioxide emitters	CO ₂ emitter pad, CO ₂ emitter and antimicrobial pad, box system with CO ₂ emitter	Reduce the microbial load, inhibits moulds, gram-negative bacteria and their spoilage, preserve food quality	Roasted ground, bakery products, coffee, snack foods, nuts, dried meat, sponge cakes, fish	Ageless® Verifresh® FreshPax CO ₂ ® Fresh Pads CO2Scav FreshMax UltraZap® Xtenda Pak pads SUPERFRESH
Ethylene scavengers	Sachets, films	Control of fruits and vegetable's ripening, reduce deterioration and increase the shelf life	Horticultural products mainly climacteric fruits- mango, apple, banana and also vegetables	BioXTEND® WiseFresh® Profresh Everfresh OxyGuard® PEAKfresh® Keep-it-Fresh FreshPax Goldripe
Moisture scavengers	Sachets, desiccant packets, mats, tray, liquid absorbers	Control of excess moisture inside food packages, maintenance of food quality, inhibit microbial growth on surface and extend shelf life	Dried foods, cereals, bakery products, meat, fish, poultry, snack foods, cut fruits and vegetables	Drymax® Dri-Loc® DryPak™ Norfresh® MoistCatch Keep-it-Dry TenderPac® Fresh-R-Pax®
Antimicrobial packaging	Antibiotics, fungicides, silver zeolite containing films, sachets, labels, sheets, and trays, antifungal coating	Inhibition of microorganism growth, extend shelf life, reduce post-harvest decay, maintain storage quality	Cheese, bakery products, meat products, fresh fruits and vegetables	Zeomic® Biomaster® Aglon® Microban® Irgaguard® Surfacine® IonPure® Bactiblock® Biomaster® Sanic Films SANICO®
Antioxidants	Film coating	Inhibition of oxidation processes	Cereal products, meats, fish, nuts	Oxbar Duralox ATOX

Potassium permanganate embedded in silica gel is a widely used ethylene absorber (Cierpiszewski, 2016) ^[2]. When ethylene is oxidized, the potassium permanganate changes color from purple to brown, indicating its effectiveness. Silica gel ethylene absorbers are usually enclosed in sealed sachets, ethylene-permeable packaging to avoid direct contact with the packaged product. Another approach involves incorporating zeolite clay with an ethylene absorber into packaging films. This design facilitates the absorption of ethylene and carbon dioxide from the package headspace. However, this solution can compromise packaging transparency.

Activated carbon combined with palladium chloride acts as a highly efficient ethylene absorbent. This absorbent has been shown to significantly delay fruit softening in minimally processed bananas and kiwi fruit and counteract chlorophyll degradation in spinach. Potassium permanganate-based systems (Ethylene Control, Power Pellet, and Retarder) are available as sachets or embedded as finely powdered minerals within polymeric matrices. Zeolite-based systems (PEAKfresh® and EvertFresh) incorporate zeolites within polymeric materials to absorb ethylene.

3. Limitations

Despite the growing interest and innovation in active packaging technologies, several critical limitations constrain their widespread commercial application. A key concern is the migration of active compounds such as nanoparticles, antimicrobials, and antioxidants, into food matrices. These migrations can pose potential health risks, especially when nanomaterials or synthetic compounds are involved. The toxicological profiles of many active agents, including silver nanoparticles and synthetic antioxidants like BHA and BHT, remain inadequately understood, raising significant concerns regarding consumer safety (Maisanaba *et al.*, 2017;

Kuswandi, 2020) ^[17, 15]. Another significant challenge lies in the lack of harmonized global regulations. The legal frameworks for approving active packaging materials vary across regions, with the European Union adopting more stringent regulations than other parts of the world (Janjarasskul & Suppakul, 2018) ^[11]. This regulatory uncertainty impedes industry-wide adoption and discourages investment in novel AP technologies.

Consumer acceptance is also a limiting factor. Studies indicate that many consumers are wary of chemical additives in packaging, particularly if labeling is unclear or implies chemical migration (Prasad & Kochhar, 2014) ^[20]. The presence of labels such as "DO NOT EAT" on sachets or pads, while necessary, may further reinforce distrust and reduce marketability of AP solutions. From an economic standpoint, cost and scalability continue to hinder large-scale industrial adoption. Many active components, such as essential oils, natural extracts, and metallic nanoparticles, are costly to produce and difficult to incorporate uniformly into packaging materials without sophisticated processing methods (Riaz *et al.*, 2020; Deshmukh *et al.*, 2022) ^[21, 4]. Additionally, the environmental impact of non-biodegradable polymers used in some AP systems may conflict with increasing sustainability demands, unless biopolymer-based alternatives are used (Gaikwad *et al.*, 2019) ^[8].

4. Future Perspectives

The future of active packaging in the food industry looks promising, with several emerging trends and technologies poised to shape the market. Some potential future directions include: Incorporating nanoparticles into active packaging systems could enhance their functionality and effectiveness; developing biodegradable active packaging materials could reduce environmental concerns and promote sustainability; integrating sensors, RFID tags, and other smart technologies

into active packaging could enable real-time monitoring and tracking of food products; designing active packaging systems tailored to specific food products, storage conditions, and consumer preferences could optimize food safety and quality, regulatory frameworks; establishing standardized regulatory frameworks for active packaging could facilitate industry-wide adoption and ensure consumer safety; educating consumers about the benefits and proper use of active packaging could increase acceptance and drive demand, sustainable supply chains; implementing active packaging solutions that prioritize sustainability, recyclability, and waste reduction could transform the food supply chain.

5. Conclusion

Active packaging represents a significant advancement in the food industry, providing a reliable solution to enhance food safety, quality, and shelf life. The various types of active packaging systems, including oxygen scavengers, ethylene absorbers, moisture controllers, and antimicrobial packaging, have shown considerable promise in addressing the challenges faced by the food industry. As the demand for safe, healthy, and sustainable food products continues to rise, active packaging is expected to contribute significantly to shaping the future of the food industry. However, further research is needed to address current limitations, ensure compliance, and improve consumer acceptance. By adopting active packaging solutions, the food industry can reduce food waste and packaging use while supporting a more sustainable food system.

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• Data Availability Statement

No new data were generated or analyzed in this study. All information used in this review was obtained from previously published sources, which are appropriately cited in the manuscript.

• Ethics Statement

Ethical approval was not required for this study because it is based solely on the review of existing published literature and does not involve human or animal participants.

• Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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