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Research Progress on Multi-Mechanism Synergistic Antibacterial Preservation of Intelligent Fresh-Keeping Films

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Abstract. The global issue of food waste is severe, with food spoilage being a primary contributor. Although traditional preservation technologies offer certain benefits, they face limitations such as finite effectiveness and environmental unfriendliness. Intelligent fresh-keeping films represent a significant innovation in the food packaging sector, transitioning from single-barrier functions towards multi-mechanism synergistic functionalities. This paper systematically reviews recent research progress on the antibacterial and preservation capabilities of intelligent fresh-keeping films, elucidating their mechanisms of environmental perception, dynamic antibacterial action, and preservation maintenance. The temporal, spatial, and targeted synergy of multiple mechanisms enhances the overall efficacy of these films. Despite ongoing challenges related to cost and stability, the integration of materials science, nanotechnology, and the Internet of Things (IoT) holds promise for transforming intelligent fresh-keeping films from passive packaging into active management systems, providing crucial technological support for adding value to the food supply chain and promoting sustainable development.

Keywords: Fresh-keeping film, Antibacterial mechanism, Preservation function, Synergistic effect, Dynamic response

1. Introduction

The global problem of food waste is increasingly prominent. According to estimates by the Food and Agriculture Organization of the United Nations (FAO), approximately one-third of all food produced is lost or wasted annually within the supply chain, with food spoilage being a major cause [1]. Traditional food preservation techniques, such as refrigerated storage, vacuum packaging, and modified atmosphere packaging (MAP), while extending shelf life to some extent, suffer from limitations including finite effectiveness, restricted applicability, and environmental concerns. Furthermore, the most widely used petroleum-based plastic packaging materials are non-biodegradable, leading to severe “white pollution” and potential health risks from microplastics [2]. Consequently, developing intelligent packaging technologies that combine high-efficiency preservation functions with environmental sustainability has become a research hotspot in the food industry.

Intelligent fresh-keeping films are a significant achievement in the transition of food packaging from “passive barrier” to “active and intelligent”. Unlike traditional packaging that merely provides

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physical protection, intelligent active packaging technology can sense, respond to, and dynamically regulate the food and its surrounding environment. The fundamental principle involves incorporating responsive functional components into the packaging film material, enabling it to delay spoilage processes and enhance food freshness and safety through color changes, signal feedback, or the release of active substances in response to changes in conditions such as pH, temperature, humidity, or gases [2]. This type of packaging not only monitors food status in real-time but also actively intervenes in food spoilage, representing a key technology for reducing food loss and enabling the transition to green packaging.

In recent years, researchers worldwide have conducted extensive studies on the functional materials and structural design of intelligent packaging. Regarding materials, natural polymers such as proteins and polysaccharides have been widely utilized as substrates for preparing composite films. Compared to synthetic polymers, these materials offer greater biocompatibility and biodegradability, and demonstrate advantages in mechanical properties, barrier performance, and active functionalities [3]. In terms of functional mechanisms, researchers have developed functional materials capable of dynamic responses to environmental signals like pH, temperature, humidity, and gases. For instance, Pickering Emulsions (PEs), which utilize solid particles instead of traditional surfactants to stabilize the emulsion system, provide a novel approach for the efficient loading and controlled release of active substances [4-5]. Meanwhile, Janus films based on asymmetric wettability design enable directional liquid transport, preventing spoilage in aquatic products caused by drip loss [6-8]. Concurrently, advancements in nanocomposite technology have further enhanced the performance of intelligent packaging. By incorporating nanofillers or using intercalation composite techniques to combine rigid nanomaterials with flexible biopolymers, these approaches not only significantly improve the mechanical properties, gas barrier properties, and thermal stability of the films but also endow them with the functional characteristics of nanomaterials and the biodegradability of biopolymers. Such bionanocomposites are considered important alternatives to petrochemical plastics and show broad application prospects [1].

2. Environmental perception mechanisms of intelligent fresh-keeping films

2.1. pH-response mechanism

Food spoilage is accompanied by significant pH changes. For example, during the initial spoilage of aquatic products, pH decreases due to lactic acid accumulation, while in later stages, pH increases due to protein degradation, generating amine compounds (e.g., Total Volatile Basic Nitrogen - TVB-N). pH-responsive packaging films convert these changes into detectable signals, enabling non-destructive monitoring of food freshness [9]. Intelligent films achieve this response by integrating pH-sensitive materials, such as natural anthocyanins, curcumin, synthetic dyes, or functional polymers.

Natural pigments like anthocyanins and curcumin can serve as pH indicators, their colors changing significantly with pH, while also possessing certain antioxidant and antimicrobial activities [2]. For instance, anthocyanins in salmon packaging undergo a color transition from purplish-red to grayish-purple and finally to grayish-brown over storage time, intuitively reflecting quality changes [10]. Khan et al [11] combined copper-based Metal-Organic Frameworks (MOFs) with red cabbage anthocyanins to create a gelatin-carrageenan composite film, achieving a sensitive response across a wide pH range and triggering the release of antibacterial agents, forming an integrated “sense-response-protect” mechanism. Recent studies indicate that alizarin exhibits color

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changes from yellow to pink to purple within the pH range of 2-12, which corresponds to the pH range associated with meat spoilage, offering a new option for freshness monitoring [12].

However, natural pigment pH indicators often suffer from poor stability and complex extraction processes, while synthetic dyes pose potential safety risks [13]. Carbon quantum dots (CQDs) have also emerged as ideal pH-responsive materials due to their tunable optical properties, biocompatibility, and low toxicity. Their fluorescence and colorimetric changes can be induced by surface protonation/deprotonation or electron transfer [14].

2.2. Temperature-response mechanism

Temperature is a critical factor affecting the rate of food spoilage. Temperature-responsive packaging materials primarily operate based on the following mechanisms: (1) thermal expansion and contraction effects; (2) heat absorption and release by phase change materials; (3) phase transition of thermosensitive polymers; (4) integration with thermal sensors for monitoring and regulation [15]. For example, poly(N-isopropylacrylamide) (PNIPAM) undergoes a hydrophobic-hydrophilic transition upon temperature increase, enabling temperature-controlled release of antimicrobial agents [16]. Shen et al [17] loaded thymol into a Covalent Organic Framework (COF) and embedded it into polycaprolactone (PCL) nanofibers; the resulting film exhibited temperature-responsive release behavior above 40°C. Douaki et al [18] designed an electrospun film containing a PNIPAM release layer that accelerated the release of cinnamon essential oil at elevated temperatures, effectively inhibiting microbial proliferation induced by temperature rise.

2.3. Gas-response mechanism

Food spoilage is often accompanied by the release of characteristic gases such as CO_2, C_2H_4, H_2S, and NH_3. Gas-responsive intelligent packaging films can achieve specific recognition and response to target gases through functional materials. For instance, MOF materials can selectively adsorb specific gas molecules, triggering structural or chromogenic changes, thereby enabling non-destructive monitoring of food quality or triggering active controlled-release functions. Research also indicates that bio-composite materials based on protein-polysaccharide interactions are suitable for gas-responsive packaging; the interaction between active components and food materials can effectively modulate the gas composition within the package, thus influencing food preservation [19]. Furthermore, some polymer materials possess humidity regulation capabilities, absorbing moisture in high-humidity environments to inhibit microbial growth and releasing moisture under low-humidity conditions to reduce food desiccation, indirectly optimizing the gaseous microenvironment within the package and further enhancing preservation effect [15].

2.4. Humidity-response mechanism

Humidity is a key factor affecting food preservation. High-humidity environments can lead to extensive microbial proliferation, while excessive dryness accelerates moisture loss in food, affecting sensory and nutritional quality [20-21]. Humidity-responsive intelligent films can dynamically regulate the internal micro-environment of the package through moisture absorption or release properties and can be combined with humidity sensors for precise monitoring [15]. This type of packaging can actively adjust film structure or release functional active components based on ambient humidity changes, delaying spoilage and thereby extending shelf life [2]. For example, Cheng et al [22] developed a polyvinyl alcohol/chitosan (PVA/CS) nanofibrous membrane that

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responsively releases 4-terpineol at 98% relative humidity (RH). Guo et al [23] embedded gold nanoparticles in cyclodextrin-based MOF and hydrophobic polydimethylsiloxane (PDMS)to create a composite film that releases antimicrobial agents under high humidity conditions, effectively inhibiting microbial growth. Protein-polysaccharide composite materials, due to intermolecular hydrogen bonding and ionic interactions, not only enhance the structural stability of the film material but also exhibit excellent humidity-responsive behavior and barrier properties, performing well in humidity regulation [19].

3. Dynamic antibacterial mechanisms of intelligent fresh-keeping films

3.1. Active antibacterial strategies

3.1.1. Controlled release of antimicrobials

The core of active antibacterial strategies involves the targeted, controlled release of antimicrobial active substances triggered by sensing changes in environmental signals such as humidity, temperature, or gas composition. Natural antimicrobials like essential oils (EOs) are widely studied due to their high safety profile and broad-spectrum antibacterial properties; their volatile components can create an antibacterial "atmosphere" on the food surface, inhibiting various spoilage microorganisms without direct contact [24-26]. Taking zein/peach gum film as an example, it not only possesses good mechanical and thermal stability but also effectively inhibits the growth of Staphylococcus aureus and Escherichia coli [24]. Protein-polysaccharide composite materials serve as ideal carriers for essential oils and other active agents due to their eco-friendliness and biodegradability. Their barrier and controlled-release properties can be further enhanced through additives like nanofillers, lipids, or waxes [19].

Humidity change is a significant trigger for release. Under high humidity conditions, molecular interactions between active components and the carrier are weakened, promoting the rapid release of antimicrobial ingredients such as cinnamaldehyde and thyme essential oil, thereby achieving humidity-responsive antibacterial action [27-28]. Studies show that such moisture-driven controlled-release systems can completely inhibit the growth of S.aureus and Aspergillus niger at 98% RH [28].

Besides essential oils, natural polyphenols like flavonoids also exhibit good antioxidant and antibacterial synergistic properties. For instance, sodium alginate-carrageenan composite films containing peanut shell flavonoids, while enhancing mechanical and barrier properties, effectively delayed microbial growth and lipid oxidation in pork, extending the shelf life from 6 to 12 days [29]. This indicates that through the combination of controlled release and multi-functional active agents, intelligent fresh-keeping films can achieve dual improvement in food preservation and safety.

3.1.2. Photocatalytic antibacterial action

Photocatalytic technology offers a non-contact, efficient, and repeatedly activatable antibacterial pathway for intelligent packaging. Its mechanism primarily relies on photocatalytic materials (e.g., TiO_2) generating reactive oxygen species (ROS), including hydroxyl radicals (-OH), superoxide anions (O_2^-), etc., under UV or visible light. These ROS can damage microbial cell membranes and DNA, achieving efficient sterilization. The TiO_2-anthocyanin composite film prepared by Sani et al [30] increased mechanical strength and barrier properties while achieving an inhibition rate of up to 92.3% against S.aureus, demonstrating excellent photocatalytic antibacterial potential. Photocatalytic films not only enable immediate sterilization but also possess the advantage of being

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activatable multiple times, making them particularly suitable for surface antibacterial applications on perishable foods like meat products, fruits, and vegetables.

3.2. Passive barrier strategies

3.2.1. Enhanced physical barrier

Passive antibacterial action primarily relies on the inherent physical barrier properties of the film material to inhibit microbial growth. Enhancing the density of the film material through nanocomposite technology can effectively delay the migration of oxygen, water vapor, and small molecules, preventing the formation of conditions required for microbial proliferation. Protein-polysaccharide composite films exhibit outstanding mechanical strength, flexibility, and barrier properties. The addition of fillers such as nanocellulose or nanoclays can further prolong the gas diffusion path, significantly enhancing barrier performance [3,31]. For example, soy protein films possess strong gas and oil barrier capabilities but are sensitive to moisture; composite modification with polysaccharides can effectively compensate for this defect, expanding their practical application potential [19].

3.2.2. Surface anti-adhesion

Surface micro-nano structure modification can impart hydrophobicity and anti-adhesion properties to the film material, reducing the attachment of bacteria and moisture on the surface. Zein films exhibit excellent water resistance due to the high proportion of hydrophobic groups in their amino acid residues, effectively reducing microbial adhesion on the film surface [12]. This strategy draws inspiration from the “lotus effect”, achieving physical anti-adhesion antibacterial effects and extending food shelf life by constructing micro-nano structures or layers of low surface energy materials.

4. Preservation maintenance mechanisms of intelligent fresh-keeping films

As shown in Figure 1, intelligent fresh-keeping films precisely monitors the changes in food status through environmental perception mechanisms, combines dynamic antibacterial mechanisms to achieve active and passive coordinated prevention and control of microbial growth, and relies on humidity and gas regulation mechanisms to maintain a stable micro-environment inside the packaging, thereby building an integrated food preservation system of "perception - response - protection.

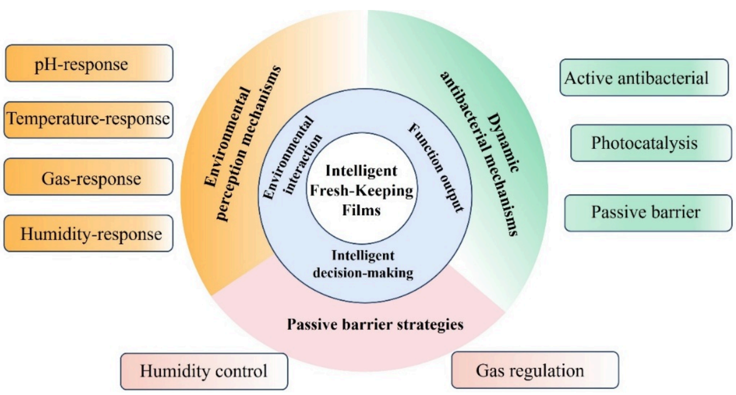

Figure 1. From environmental perception to dynamic adjustment of intelligent fresh-keeping films

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4.1. Humidity regulation mechanism

Humidity is a crucial factor affecting food spoilage and quality. Intelligent fresh-keeping films optimize the environment through bidirectional humidity regulation: absorbing excess moisture under high humidity conditions to inhibit microbial growth, and releasing moisture appropriately under low humidity conditions to prevent food desiccation [32]. For instance, the highly water-absorbent polymer peach gum (PG) not only possesses good film-forming and adsorption capacities but also exhibits free radical scavenging activity, making it suitable for use in hygroscopic food packaging [3]. Furthermore, protein-polysaccharide composite materials show advantages in humidity regulation. Their internal structure, stabilized by various mechanisms such as hydrogen bonding, ion-dipole interactions, chemical cross-linking, and hydrophobic interactions, also endows the material with moisture absorption and retention capabilities, thereby extending food shelf life [19].

4.2. Gas regulation mechanism

Regulating the gaseous environment is an important approach for intelligent films to delay food respiration and oxidative deterioration. Actively adjusting the concentrations of O_2, CO_2, and C_2H_4 within the package can effectively slow down spoilage processes. For example, plant protein/polysaccharide composite films exhibit excellent gas selectivity, with CO_2/O_2 selectivity coefficients potentially exceeding 100, enabling the creation of a high-CO_2, low-O_2 microenvironment that delays the ripening and senescence of perishable fruits like strawberries and cherries [33]. Some intelligent films can also actively adsorb ripening agents like ethylene, further optimizing the micro-atmosphere conditions through selective gas permeable structures or added adsorbents.

Active bio-composite films not only possess good water vapor and oxygen barrier properties but can also regulate the release of active components, thereby inhibiting the overly rapid migration of moisture and oxygen, slowing down respiration, and extending shelf life [19]. Notably, natural polysaccharide and protein-based edible films can also serve directly as edible coatings for food. Their selective permeability to O_2 and CO_2 can effectively reduce the respiration rate of fruits and vegetables while avoiding anaerobic respiration, significantly enhancing preservation effects [34].

5. Synergistic effects of antibacterial and preservation functions

The intelligent cling film significantly enhances its dynamic adaptability to the food spoilage process and overall preservation efficiency through the synergistic effects of timing, spatial considerations, and targeted interventions, as illustrated in Figure 2.

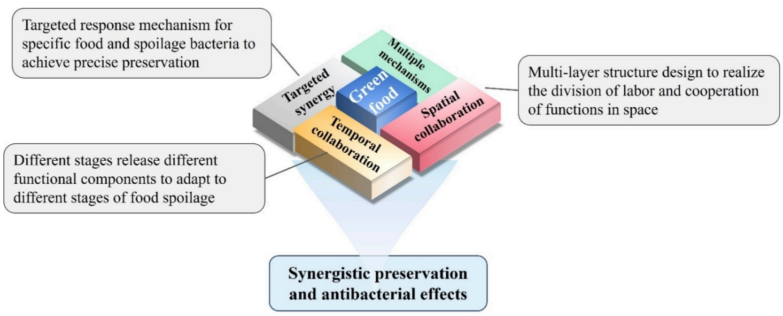

Figure 2. Multi-mechanism synergistic framework of intelligent fresh-keeping films

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5.1. Temporal synergy

The functional release of intelligent films often exhibits multi-stage synergistic characteristics. During the initial storage period, the physical barrier and the release of a small amount of active agent can inhibit microbial growth. When pH changes occur due to temperature fluctuations or microbial proliferation, it triggers the release of a larger quantity of antimicrobials to enhance antibacterial action. Meanwhile, humidity and gas regulation mechanisms continuously maintain food quality throughout the storage period. Protein-polysaccharide bio-composite materials, owing to their good structural designability, can achieve dynamic coordination of antibacterial and preservation functions at different stages, providing more flexible response capabilities compared to traditional packaging [19].

5.2. Spatial synergy

Multi-layer structural design enables the division of labor and synergy of functions in the spatial dimension. For instance, bilayer film structures offer superior physical properties and water barrier capability compared to monolayer films [12]. Wang [24] developed a multilayer bio-composite film utilizing PG as the moisture-absorbing inner layer, zein (ZN) as the high-barrier outer layer, and a middle layer (ZN/PG) to regulate the release of thirteen-spice essential oil (TSEO), achieving multi-dimensional synergy between antibacterial action and preservation. Another typical case is the Janus film, whose hydrophilic/hydrophobic asymmetric structure enables directional liquid transport, effectively preventing spoilage caused by drip loss in aquatic product packaging while keeping the surface dry [6-8]. Such spatial synergy strategies provide effective pathways for the multi-functional integration and structural innovation of intelligent films.

5.3. Targeted synergy

Targeted response mechanisms designed for specific foods and spoilage microorganisms facilitate precise preservation. Enzyme-responsive active packaging specifically blocks key endogenous enzyme activities through the slow release of inhibitors (e.g., phenolic compounds, plant extracts) or metal ion chelation, thereby slowing down spoilage processes [2,35]. For example, lysozyme can specifically hydrolyze glycosidic bonds in bacterial cell walls, exhibiting significant inhibitory effects against Gram-positive bacteria. The thymol-loaded nanomaterial developed by Dong et al [36] can cleave disulfide bonds under the action of specific bacterial enzymes, achieving on-demand release of active substances. Such “sense-and-release” mechanisms based on the recognition of spoilage markers not only improve antibacterial efficiency but also reduce interference with food quality and beneficial microbiota.

6. Synergistic effects of antibacterial and preservation functions

In recent years, materials for intelligent fresh-keeping films have continuously innovated. Metal-Organic Frameworks (MOFs) are advantageous for loading functional dyes and active components due to their high specific surface area and tunable pore size. Carbon Quantum Dots (CQDs), derived from green sources with good biocompatibility, possess UV shielding, antioxidant, and antibacterial properties. Pickering emulsions and Janus films provide new platforms for the loading and directional transport of active components. These materials generally exhibit biocompatibility, biodegradability, and potential for multi-functional integration. Protein-polysaccharide bio-composite materials are a research focus, as their film-forming properties and responsiveness can be

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significantly enhanced through interactions like hydrogen bonding and cross-linking. Furthermore, incorporating additives such as metal nanoparticles, polyphenols, and probiotics can further improve the antioxidant and antibacterial activities of the film materials, meeting the dual needs of food safety and shelf-life extension [37].

Despite the significant application potential of intelligent fresh-keeping films, their large-scale adoption still faces multiple challenges. Firstly, cost and scalability issues are prominent; nanomaterials and intelligent sensors are expensive, and preparation processes like layer-by-layer casting and electrospinning are complex, affecting industrial production efficiency. Secondly, under extreme temperature and humidity conditions, the stability and reliability of film materials are insufficient, and active components are prone to deactivation and migration [2,19]. Furthermore, the migration patterns and biosafety of novel materials like CQDs and MOFs are not fully understood, and regulatory assessment systems and standardized testing methods urgently need improvement [2,12]. Simultaneously, the integration of intelligent films with multiple technologies is still in the exploratory stage, lacking unified standards and specifications [3,19]. Finally, due to the diversity of food types and spoilage mechanisms, material selection requires balancing universality and specificity [2,19].

Future development directions for intelligent fresh-keeping films should adhere to the concept of “environmental interaction - intelligent decision-making - functional output.” In terms of materials, development should focus on bio-based, biodegradable, and highly responsive materials, tailoring protein-polysaccharide blends to adapt to differences in acidity, moisture, and fat content [2,19]. Structural design should employ complex architectures like Janus, core-shell, and multi-layer to achieve spatiotemporal regulation of active components and improve the mechanical properties of the films [12]. Intelligent packaging should deeply integrate multiple technologies to achieve real-time monitoring and digital management of food quality [2,19]. Concurrently, precise research on specific food-spoilage microorganism systems should be conducted [19], and utilizing agricultural waste to prepare bio-composite films should be promoted to advance green packaging development [19].

7. Conclusion

Intelligent fresh-keeping films achieve active intervention and intelligent management of food spoilage processes by integrating three core functions: environmental perception (pH, temperature, humidity, gases), dynamic antibacterial action (controlled release, photocatalysis, barrier enhancement), and preservation maintenance (humidity regulation, gas regulation). Their high efficiency stems not only from breakthroughs in individual performances but also relies on the synergistic effects of multiple mechanisms at the temporal, spatial, and targeted levels. Although challenges remain in cost control, stability enhancement, and standardization establishment, particularly in bio-based material modification, biomimetic structural design, and intelligent system integration, the convergence of materials science, nanotechnology, the Internet of Things (IoT), and artificial intelligence is driving intelligent fresh-keeping films towards higher efficiency, safety, economy, and green sustainability. In the future, intelligent fresh-keeping films are expected to reshape food packaging paradigms, transitioning from passive containers to integrated systems capable of environmental interaction, intelligent decision-making, and functional output. They will provide key technological support for loss reduction, quality preservation, value addition, and safety within the food supply chain, promoting the deep transformation of the food industry towards intelligence and sustainability.

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