Recent Developments in Natural Biopolymer Composites for Active Food Packaging

Yawei Cai,[a,c,*] Na Sun,[b,c] Qixuan Lin,[a] Jianghe Liu,[d] and Yongjun Chen [a,*]

The transition toward a circular economy has established biodegradable polymer composites as a critical platform for active food packaging. This review systematically examines the structural design, functional mechanisms, and application performance of natural biopolymer matrices, including polysaccharides and proteins. Physicochemical coupling among polymer-network architecture, interfacial interactions, and active-agent dispersion governs the integration of antimicrobial, antioxidant, gas-barrier, UV-shielding, moisture-regulating, and stimuli-responsive functions. Particular emphasis is placed on controlled mass transfer and release kinetics at active packaging interfaces. Active-agent delivery is governed by molecular diffusion, polymer-network relaxation, carrier structure, and microenvironmental triggers such as pH, humidity, and temperature, which collectively determine the effective concentration and duration of antimicrobial and antioxidant activity. These structure–release–function relationships are further evaluated in high-moisture foods, respiring fruits and vegetables, and low-moisture or lipid-rich products. In addition, this review discusses the major constraints on industrial translation, including the migration and regulatory compliance of intentionally and non-intentionally added substances, nanoparticle safety, environment-dependent biodegradation, life cycle impacts, and thermomechanical challenges associated with continuous processing. Future development should move beyond passive material substitution toward the integrated design of active and intelligent packaging, scalable manufacturing, food-specific performance validation, and multi-objective optimization of functionality, safety, cost, and end-of-life behavior.

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Contact information: a: Packaging Materials Testing Laboratory, Shenzhen Polytechnic University, Shenzhen 518055, Guangdong, China; b: Huzhou Key Laboratory of Green Energy Materials and Battery Cascade Utilization, Huzhou University, Huzhou 313000, Zhejiang, China; c: School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150080, Heilongjiang, China; d: Industrial Training Center, Shenzhen Polytechnic University, Shenzhen 518055, Guangdong, China;
** Corresponding authors: caiyawei@szpu.edu.cn; chenyongjun@szpu.edu.cn*

INTRODUCTION

Extending food shelf life and ensuring food safety impose multi-dimensional performance requirements on modern packaging materials (Ablegue *et al.* 2025). Traditional petroleum-based polymers dominate the food packaging sector because of their low cost, excellent processing rheology, and high gas barrier properties. However, their inherent recalcitrance to degradation has caused severe ecological burdens, including solid waste accumulation, microplastic pollution, and the depletion of finite fossil resources.

Consequently, developing novel alternative materials that integrate environmental sustainability with functional efficacy has become an inevitable trend in the transition toward a circular economy (Geyer *et al.* 2017; Barrowclough and Birkbeck 2022).

Biodegradable polymers—encompassing natural macromolecules such as starch, cellulose, chitosan, alginate, and proteins, alongside certain bio-based synthetic polyesters—are regarded as highly promising matrices for packaging materials due to their renewability and biocompatibility (Atta *et al.* 2022; Dutta and Sit 2024; Megha *et al.* 2024). Nevertheless, neat natural polymer networks typically contain dense arrays of polar groups (*e.g.*, hydroxyl and carboxyl groups), resulting in pronounced hydrophilicity. This characteristic leads to significant attenuation of mechanical strength in the wet state, high water vapor transmission rates, and restricted thermal processing windows. To overcome these inherent deficiencies and meet the physical performance standards of commercial packaging, it is imperative to remodel the interfacial interactions and network topology of the materials through multi-scale composite engineering, such as nanofiller blending, chemical cross-linking, and multilayer assembly (Amin *et al.* 2022; Stoica *et al.* 2024). Broader studies of natural-fiber hybrid composites likewise indicate that fiber–matrix adhesion, reinforcement architecture, and defect evolution govern stress transfer and mechanical failure (Saleem *et al.* 2018, 2023, 2024a,b; Manikandan et al. 2026).

Building upon this foundation, active packaging refers to packaging systems that are intentionally designed to interact with the food or package headspace by releasing active compounds, absorbing or scavenging undesirable substances, or regulating the local microenvironment to maintain food quality, improve safety, or extend shelf life. This category includes antimicrobial- and antioxidant-releasing systems, oxygen and ethylene scavengers, moisture regulators, and stimuli-responsive delivery systems. In contrast, packaging that provides only containment, mechanical support, or passive gas and moisture barriers without a deliberately designed interaction with the food or headspace is not classified as active packaging. Intelligent packaging that solely monitors food condition is also conceptually distinct unless it is integrated with an active intervention function.

Within this framework, a central focus of this review is the controlled release of active agents, because preservation efficacy depends not only on the intrinsic activity of the incorporated compounds but also on their spatial and temporal delivery at the food–package interface. By incorporating essential oils, natural polyphenols, inorganic nanoparticles, or microporous framework carriers such as metal–organic frameworks (MOFs) and zeolitic imidazolate frameworks (ZIFs) into biodegradable matrices, composite systems can establish dynamic protection mechanisms at the food-contact interface (Angeli *et al.* 2025; Jiang *et al.* 2025b; Zhang *et al.* 2024d). These mechanisms involve multiple physicochemical processes. Antimicrobial activity may be achieved through cell-envelope disruption and the induction of reactive oxygen species (ROS), whereas oxidative deterioration can be suppressed through radical scavenging, ultraviolet (UV) shielding, and the catalytic or adsorptive removal of undesirable headspace gases, including oxygen and ethylene (Alfei *et al.* 2024; Bai *et al.* 2024). The duration and effectiveness of these functions are strongly governed by mass-transfer and controlled-release processes, including molecular diffusion, polymer-network relaxation, carrier–matrix interactions, and responses to microenvironmental stimuli such as pH, relative humidity, and temperature (Kuai *et al.* 2021; Ahmed *et al.* 2022).

For heterogeneous food systems, the structural design of active packaging must be precisely tailored to their specific physiological and metabolic characteristics. For high-moisture and lipid-rich meat and seafood products, the design of the packaging network

focuses on exudate control, the stable release of interfacial antioxidants, and broad-spectrum antimicrobial activity (Constantin *et al.* 2026). Conversely, for fresh-cut fruits and vegetables with highly active respiratory metabolism, it is necessary to optimize the gas permeation selectivity of coatings or films, establishing a thermodynamic balance among water transpiration, O_2/CO_2 exchange rates, and ethylene scavenging (Faisal *et al.* 2025; Bin *et al.* 2026). This quantitative matching of "matrix structure to preservation function" is central to achieving effective packaging intervention.

Although laboratory-scale solution casting studies have extensively validated the feasibility of the above-mentioned strategies, the industrial translation of biodegradable active packaging remains constrained by multi-dimensional factors. First, the incorporation of functional components induces complex interfacial substance migration issues, necessitating strict adherence to regulatory frameworks to evaluate the compliance of intentionally added substances (IAS) and non-intentionally added substances (NIAS) generated from polymer degradation (Miralles *et al.* 2025). Second, the environmental fate of the materials cannot be simply equated with "biodegradable," but must be systematically quantified by integrating degradation kinetics in specific end-of-life pathways (*e.g.*, soil degradation, industrial composting) with life cycle assessment (LCA). Additionally, the scale-up of the manufacturing process faces significant thermomechanical challenges (Shen *et al.* 2023b; Pamakštys *et al.* 2026). Specifically, when transitioning solution-based formulations to continuous melt extrusion processes (*e.g.*, film blowing, cast extrusion) that entail high-temperature and high-shear flow fields, it is critical to effectively suppress the volatilization loss and thermal degradation of active components, as well as phase separation within the matrix (Patil *et al.* 2024).

To ensure a focused and up-to-date review, relevant studies were mainly identified from the Web of Science, Scopus, and PubMed databases using keywords related to natural biopolymers, active food packaging, controlled release, antimicrobial and antioxidant functions, biodegradation, and food preservation. Peer-reviewed studies directly addressing food-packaging applications and reporting relevant material properties or preservation performance were included, whereas duplicate, non-peer-reviewed, unrelated, or insufficiently documented studies were excluded.

Against this background, this review systematically outlines recent advances in biodegradable polymer composites within the active food packaging domain. This article first summarizes the structural characteristics and composite modification strategies of representative natural biopolymer matrices. Particular emphasis is then placed on controlled mass transfer and release kinetics at active packaging interfaces, including the effects of molecular diffusion, polymer-network relaxation, carrier architecture, and pH-, humidity-, and temperature-responsive behavior. The associated antimicrobial and antioxidant mechanisms are subsequently discussed in relation to the availability and duration of active compounds. The review further evaluates the preservation performance of these systems in heterogeneous foods, including high-moisture products, respiring fruits and vegetables, and low-moisture or lipid-rich foods. Finally, it systematically examines the critical bottlenecks constraining technological translation, including substance-migration compliance, environmental degradation kinetics, and thermomechanical scale-up challenges, with the aim of providing a theoretical basis for the development of multifunctional packaging materials with high industrial viability and environmental sustainability.

Natural Biopolymer Platforms and Structural Engineering

Starch matrices

As one of the most abundant natural macromolecular carbohydrates on Earth, starch is primarily extracted from plant tissues such as corn, potato, cassava, and wheat. Chemically, starch is a polysaccharide that is made up of polymerized D-glucopyranose units, mainly comprising two macromolecular conformations: amylose and amylopectin. Amylose, connected primarily by α-1,4-glycosidic bonds, forms a relatively linear helical structure and serves as the core component providing the matrix with excellent film-forming properties, flexibility, and mechanical strength. Amylopectin, containing numerous α-1,6-glycosidic branches on the main chain, possesses a highly branched structure that typically leads to poor film-forming ability but significantly influences the viscosity, crystallization behavior, and gelation process of the system. The inherent differences in the ratio of amylose to amylopectin among different botanical sources (amylose content typically ranges from 15% to 30%) fundamentally determine their baseline film-forming characteristics. Furthermore, native starch exists as semi-crystalline granules that are insoluble in cold water. To transform it into a continuous film matrix, heating and shearing in the presence of plasticizers (such as water, glycerol, or sorbitol) are usually required. This gelatinization process effectively disrupts the hydrogen bond network within the starch granules, allowing the polymer segments to disentangle and rearrange, thereby forming thermoplastic starch (TPS), which has processing potential or homogeneous film-forming solutions.

Based on these material properties, starch has become one of the most widely used matrices among natural polysaccharide food packaging materials, owing to its abundant sourcing, low cost, complete biodegradability, and high formulation compatibility. Its structural characteristics make it highly suitable as a loading platform for essential oils, polyphenols, plant extracts, and nanofillers. However, because the starch polymer chains are rich in hydroxyl groups, pure starch films generally exhibit strong hydrophilicity, high water solubility, and poor wet mechanical stability. This limits their application in practical packaging scenarios that require a comprehensive balance of mechanical properties, barrier performance, and storage stability. Therefore, recent research focus has gradually shifted from exploring single film-forming capabilities to enhancing the structural stability of the matrix through composite modification strategies and endowing it with active preservation and controlled-release functions.

For essential oil-incorporated active starch films, Wang *et al.* (2022) demonstrated using a cassava starch/geranium essential oil system that as the essential oil content increased to 2%, the tensile strength of the films decreased from 8.12 ± 0.30 MPa to 3.09 ± 0.11 MPa, while the elongation at break increased from 41.59 ± 1.67% to 72.84 ± 3.55%. Concurrently, the inhibition zone areas against *Escherichia coli*, *Staphylococcus aureus*, and *Listeria monocytogenes* reached 99.14 ± 3.21, 125.31 ± 2.58, and 126.57 ± 2.45 mm², respectively. Criollo-Feijoo *et al.* (2024) introduced oregano essential oil into cassava starch and cassava bagasse starch films. Their results indicated that at an essential oil content of 3%, the water vapor permeability values of the two types of films were 6.32×10^{-14} and 5.73×10^{-14} kg·m/(m²·s·Pa), with maximum stresses of 0.19 and 0.39 MPa, respectively; the total phenol content and antioxidant activity were significantly enhanced, exhibiting obvious inhibitory effects against pathogenic bacteria. Bhatia *et al.* (2025) observed significant improvements in DPPH and ABTS scavenging rates after adding juniper berry essential oil to potato starch/pectin films, along with inhibitory effects on

strains such as *Pseudomonas aeruginosa*. Furthermore, Chysirichote *et al.* (2025) constructed active films using acetylated rice starch (degree of substitution, DS = 1.8) and essential oil, which reduced the system's water solubility to 15.3% and water vapor permeability to 10×10^{-11} g·m^{-1}·s^{-1}·Pa^{-1}, and extended the shelf life of fried pork rind at 30 °C from 37.8 days to 57.7 days. These results indicate that the incorporation of essential oils primarily endows starch films with antimicrobial and antioxidant functions while increasing matrix flexibility; however, without interfacial compatibilizers or cross-linking designs, it typically results in a reduction of the mechanical strength of the matrix.

The introduction of polyphenols and plant extracts is frequently used to simultaneously improve the antioxidant properties, UV-shielding capability, and interfacial compactness of the films. Luo *et al.* (2022) introduced tea polyphenols and MgO nanoparticles into potato starch films, which significantly improved the moisture content (decreased to 11.21%), water solubility (decreased to 16.56%), and water vapor permeability (decreased to 9.07×10^{-11} g·m^{-1}·s^{-1}·Pa^{-1}) of the films. Miao *et al.* (2021) developed active films *via* a "tea polyphenol-loaded porous starch" strategy, discovering that the incorporation of porous starch resulted in a tea polyphenol release of 83% at 240 min, demonstrating a superior sustained-release effect compared to the direct addition system (which released 88% at 180 min). Moreover, the composite film containing 10% tea polyphenols exhibited the best comprehensive physicochemical properties. These two studies indicate that starch can not only serve as a continuous phase matrix but also participate in regulating the delivery behavior of active molecules through its microscopic pore structure.

Regarding natural pigments and fruit/vegetable byproduct extracts, Luz *et al.* (2023) prepared starch films containing jabuticaba peel phenolic extracts, presenting distinct integrated active and intelligent features. The optimized films exhibited a DPPH scavenging percentage of 91.01 ± 0.5%, a tensile strength of 16.3 ± 0.7 MPa, and an elongation at break of 79.7 ± 3.1%, while also possessing high transparency, UV-shielding properties, antimicrobial activity, and pH-responsive color-changing capabilities. Zhang *et al.* (2024c) introduced sweet potato peel polyphenols into sweet potato starch films, finding that under the optimized formulation, the water solubility of the pure film decreased from 90.4% to 45.9%, and the water contact angle increased from 51.7° to 82.3°. Concurrently, the water vapor and oxygen permeability significantly decreased, and the antioxidant activity substantially increased, extending the preservation period of cherry tomatoes at 4 °C to 7 days. This suggests that polyphenolic substances from food processing byproducts help to improve the hydrophobicity, gas barrier properties, and functional activity of the films.

The introduction of natural second-phase fillers is another effective approach for optimizing the starch matrix structure. Chen *et al.* (2024b) found that the water contact angle of a laver-reinforced starch film (optimized sample S7-3) increased to 114.98 ± 1.28°, and its water solubility decreased to 15.38%; meanwhile, its tensile strength, elongation at break, and Young's modulus reached 32.5 MPa, 19.0%, and 607 MPa, respectively. Raajeswari *et al.* (2025) fabricated composite films using tapioca starch, carboxymethyl cellulose (CMC), citric acid, and basil essential oil. The ultimate load of their optimized formulation reached 85.39 ± 0.26 N, with a tensile strength of 6.28 ± 0.17 MPa. In food packaging tests, the composite films containing basil oil exhibited the lowest total viable count (3.1×10^1 CFU/g) on day 120 and completely degraded in soil within 24 days. Such studies validate the coupled relationship among structure, properties, and functions, wherein compatibilizers and cross-linkers optimize the matrix structure, while

active substances provide functional properties. Notably, introducing novel two-dimensional nanomaterials offers considerable engineering potential for overcoming the mechanical and barrier limitations of starch matrices. Recently, Dong *et al.* (2024) introduced $Ti_3C_2T_x$ MXene nanoplatelets into a starch matrix for the first time, developing fully biodegradable nanocomposite films with exceptional water and oxygen barrier properties. As illustrated in Fig. 1, the hydrophilicity of the composite film was significantly suppressed with increasing MXene content.

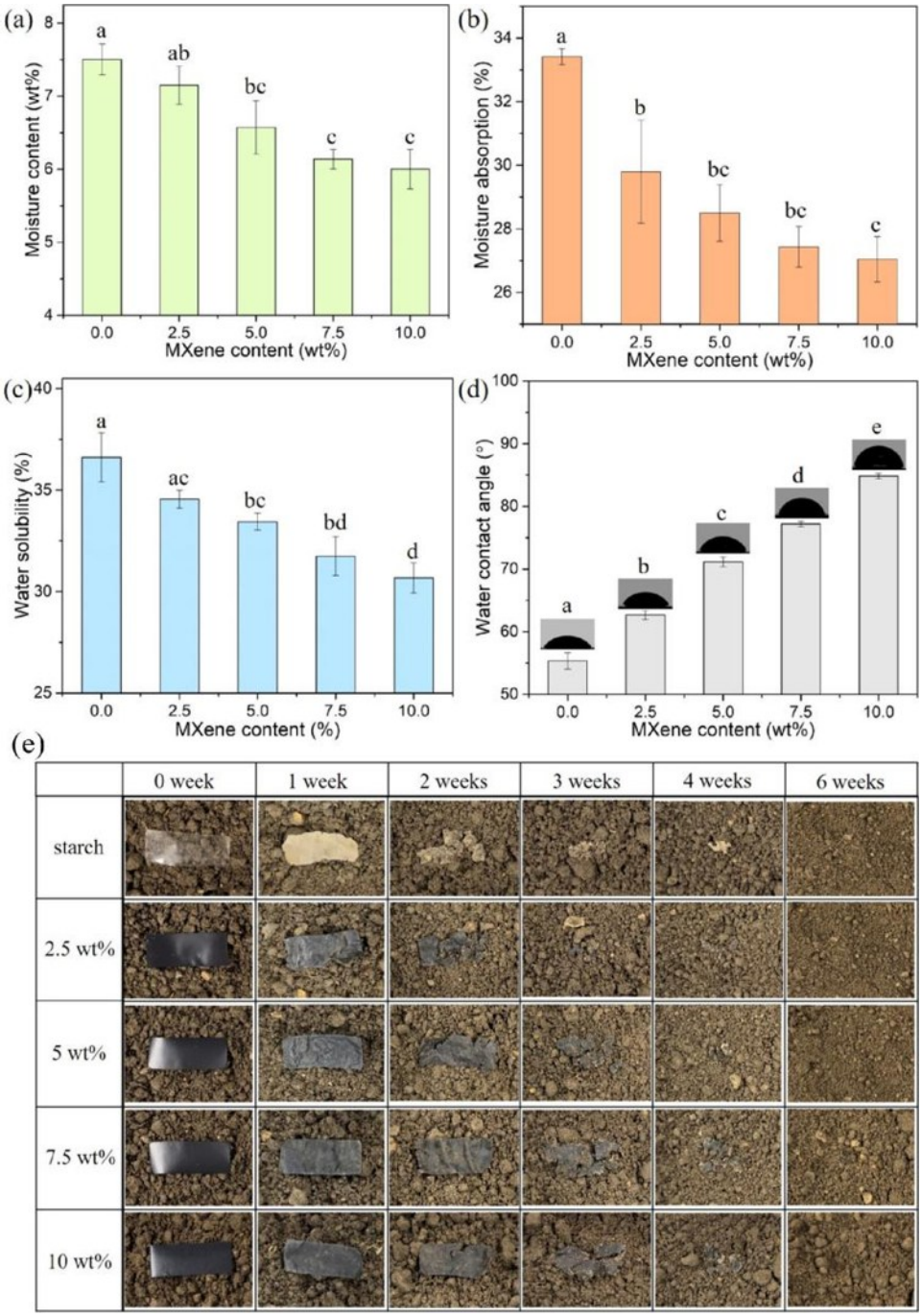

Fig. 1. (a) Moisture content; (b) moisture absorption; (c) water solubility; (d) water contact angle; and (e) soil burial test process of pure starch films and composite films with different MXene loadings. (Reproduced from Dong *et al.* (2024), CC BY 4.0).

At a 10 wt% addition level, the water contact angle of the film increased from 55.3° (pure starch film) to 84.8°, while the moisture content, moisture absorption, and water solubility exhibited systematic reductions (Figs. 1a–d). More crucially, benefiting from the dense hydrogen bond network formed within the matrix and the physical labyrinth effect (highly tortuous paths) constructed by the 2D nanosheets, the water vapor and oxygen permeability of the composite film plummeted by 92.9% and 74.0%, respectively. Mechanically, its Young's modulus surged from 456.5 MPa to 1923.6 MPa, and the tensile strength improved from 9.9 MPa to 19.1 MPa. Soil burial tests (Fig. 1e) further confirmed that the composite films could completely degrade within 6 weeks. This work demonstrates that the rational utilization of the geometric characteristics and surface chemistry of 2D nanofillers can achieve a simultaneous improvement in the "high mechanical-high barrier" performance of starch matrices, without sacrificing the natural biodegradability of the materials.

Research by Sousa *et al.* (2025) on monolayer films of TPS and olive leaf extract demonstrated that natural polyphenols could improve material performance while maintaining the continuous structure of the matrix. With the addition of 5% and 10% extract, the Young's modulus of the films increased from 0.95 ± 0.11 GPa to 1.11 ± 0.10 and 1.17 ± 0.08 GPa, respectively, and the tensile strength also increased. Fresh-cut pear preservation experiments showed that the extract-modified films could significantly reduce the browning index of the fruit. On the other hand, Cvetković *et al.* (2025) found that although the introduction of wild blackberry extract endowed the films with pH responsiveness and high antioxidant activity, it also exacerbated the hydrophilicity of the starch matrix, leading to significant increases in film moisture content, swelling capacity, and water solubility. This suggests that when designing smart responsive starch films, it is essential to comprehensively balance the matching degree between responsive functions and matrix water resistance, rather than solely relying on the "lowest permeability" as the guiding metric.

To improve wet stability, Mylkie *et al.* (2025) utilized boronated chitosan to cross-link starch films containing cannabidiol (CBD) oil, decreasing the water vapor transmission rate to 3 $g \cdot m^{-2} \cdot day^{-1}$. Under wet conditions, the attenuation of tensile strength in the cross-linked films (CS-FPBA-CBD-S) was significantly lower than that of the uncross-linked group, and they exhibited a higher free radical scavenging capacity. In contrast, Silveira *et al.* (2025) prepared low-cost bioplastic films using starch extracted from cassava processing waste. Although they demonstrated good antimicrobial ability and elongation at break (32.9%), the tensile strength was only 0.17 MPa. The results indicate that chemical cross-linking can effectively mitigate the structural instability of starch films under high-humidity conditions, whereas agricultural waste starch is more suitable as a substrate for single-use or short-lifespan active packaging.

The construction of inclusion complexes and edible coating technologies has further diversified the application forms of starch-based materials. Frangopoulos *et al.* (2025) prepared starch inclusion complex films loaded with carvacrol and ascorbic acid. In minced meat refrigeration experiments, they found that ascorbic acid helped maintain the redness of the meat, while carvacrol was more effective in inhibiting microbial proliferation. Ramadoss *et al.* (2025) developed active coatings based on pectin, potato starch, and pyrogallol, extending the shelf life of tomatoes to 21 days while effectively controlling weight loss and quality deterioration. This demonstrates that starch systems can

achieve interfacial regulations more aligned with food degradation pathways through inclusion complexes or coating structures.

In summary, representative studies from recent years indicate that: (1) the starch matrix possesses core advantages including renewability, ease of film formation, and high compatibility with natural active substances; (2) the wet mechanical attenuation and insufficient storage stability caused by its strong hydrophilicity remain its primary application bottlenecks, making composite modification a prerequisite for meeting practical application demands; (3) current design strategies are no longer limited to merely increasing the loading of active substances, but rather focus on achieving a coordinated optimization of the "structure–property–function" relationship through extract/essential oil functionalization, second-phase reinforcement, cross-linking stabilization, and inclusion complex-based controlled release techniques. In terms of application scenarios, starch-based composite films are currently best suited for fruits and vegetables, baked goods, and short-shelf-life cold chain foods; for supply chain conditions with high humidity or substantial mechanical stress loads, they typically require further compounding with cellulose, proteins, or biodegradable polyesters.

Cellulose and its derivatives

Cellulose-based materials used in active food packaging include native cellulose, nanocellulose, regenerated cellulose, bacterial cellulose, and a variety of chemically modified derivatives of cellulose. Their functions are closely related to their molecular organization and processing form. Native cellulose consists of β-1,4-linked D-glucopyranose chains assembled into highly ordered fibrillar structures through extensive intra- and intermolecular hydrogen bonding. This hierarchical organization provides high crystallinity, mechanical rigidity, and thermochemical stability, but it also results in poor solubility and limited thermoplastic processability. Consequently, native cellulose, cellulose nanofibers, and cellulose nanocrystals are commonly employed as reinforcing or network-forming phases in composite films. Chemical substitution of hydroxyl groups partially disrupts the dense hydrogen-bonding network, producing derivatives such as carboxymethyl cellulose, hydroxyethyl cellulose, hydroxypropyl methylcellulose, and methylcellulose with improved solubility and film-forming ability. Regenerated cellulose and bacterial cellulose can additionally form continuous films or three-dimensional networks, thereby extending the role of cellulose from a reinforcing component to a self-supporting packaging matrix.

The engineering performance of these cellulose-based systems is further governed by their cross-scale hierarchical assembly. As highlighted by Liu *et al.* (2022), cellulose structures extend from macroscopic plant tissues and cell walls to fibrils, crystalline and disordered domains, and molecular chains. As illustrated in Fig. 2, the coexistence of ordered crystalline regions and relatively disordered domains influences the rigidity, accessibility, and processability of cellulose. Mechanical or chemical deconstruction produces cellulose nanofibers and cellulose nanocrystals with high aspect ratios and mechanical strength, whereas microbial biosynthesis generates bacterial cellulose with a dense three-dimensional network. These structural differences provide the basis for using cellulose-based materials as reinforcing phases, continuous films, or network-forming components in active packaging systems.

Based on the material fundamentals, cellulose and its derivatives constitute a matrix system with significant structural engineering potential in natural polysaccharide-based food packaging materials. Compared to starch, cellulose matrices typically exhibit stronger

intermolecular physical cross-linking, higher structural order, and superior intrinsic oxygen barrier properties, thus presenting distinct advantages in mechanical support, transparency retention, and film-forming integrity. Furthermore, these materials are easily used in combination with polyphenols, natural pigments, antimicrobial peptides, nanocellulose, and inorganic nanoparticles to construct multifunctional composite films. However, most water-soluble cellulose derivatives retain strong hydrophilicity, which limits their water vapor barrier performance and dimensional stability under high-humidity conditions. Consequently, the current research focus has gradually shifted from merely "using cellulose to replace traditional plastics" to introducing antimicrobial, antioxidant, UV-shielding, and controlled-release functions while prioritizing the improvement of moisture resistance, all while maintaining its high-strength skeletal advantages.

Although developed for structural composites rather than food-contact films, these studies provide transferable evidence that reinforcement architecture and interfacial integrity govern stress transfer and failure. Acoustic-emission analyses of hybrid laminates and banana/ramie/epoxy composites identified matrix cracking, fiber–matrix debonding, delamination, and fiber fracture as key failure modes (Saleem *et al.* 2018, 2023, 2024a,b); hybrid stacking increased load-carrying capacity, energy absorption, and stiffness by 30.6%, 26.8%, and 35.2%, respectively (Saleem *et al*. 2024b). Biomass-derived carbon quantum dots also improved the mechanical performance of pineapple/ramie/epoxy laminates (Manikandan *et al.* 2026). In food-packaging systems, these interfacial principles must additionally be evaluated together with barrier, migration, release, and biodegradation requirements.

Carboxymethyl cellulose (CMC) is currently one of the most widely used cellulose-based active packaging materials. Roy and Rhim (2021) constructed functional films based on CMC/agar. They found that the incorporation of alizarin and grapefruit seed extract (GSE) enhanced the mechanical strength and water resistance of the films by approximately 20% and 40%, respectively, while exhibiting excellent UV-shielding, antioxidant, antimicrobial, and pH-responsive color-changing capabilities. Subsequently, Roy *et al.* (2021) further introduced cellulose nanocrystals (CNCs) and shikonin into the CMC/agar system; the resulting smart composite film achieved a tensile strength of 61.7 MPa, combining high transparency, enhanced UV-shielding performance, and significant inhibitory effects against *Listeria monocytogenes* and *Escherichia coli*. These studies indicate that polysaccharide composite systems such as CMC/agar can achieve a coordinated improvement in transparency, mechanical strength, and smart responsive activity through the introduction of appropriate amounts of active molecules and nano-reinforcement phases.

Utilizing natural agricultural/forestry byproducts or constructing multiphase cross-linked networks represents a crucial pathway in recent years to enhance the antioxidant and moisture-proof properties of CMC matrices. Lawal *et al.* (2023) introduced date seed powder into CMC films, which increased the system's thickness (from 0.11 mm to 0.15 mm), decreased water solubility (from 95.3% to 77.2%), and imparted significant free radical scavenging capacity (DPPH and ABTS scavenging rates reached 52.0% and 84.6%, respectively). Although the tensile strength slightly decreased (from 7.66 to 5.12 MPa), the elongation at break increased to 86.0%, and the composite film exhibited broad-spectrum antimicrobial activity against pathogenic bacteria, particularly showing significant inhibition against Gram-negative bacteria (such as *Salmonella typhimurium*) at high addition levels. Wang *et al.* (2025b) physically and chemically cross-linked CMC/polyvinyl alcohol (PVA) composite films using cinnamaldehyde-tannin-metal

nanoparticles, resulting in a composite film with a tensile strength of 69.8 MPa, an elongation at break of 104%, a water contact angle increased to 119°, and a maximum DPPH scavenging percentage of 89.4%. On the application side, Doveri *et al.* (2025) developed active pectin/CMC composite films with a thickness of approximately 40 to 65 μm for bread packaging, which demonstrated excellent O_2/CO_2 barrier properties. In anti-mold tests, the mold inhibition rate of the dual-active phase composite system reached 99.97%–99.998%, with active component migration well below 2.0 mg/slice. These results demonstrate that CMC is suitable as a continuous phase skeleton in multiphase composite systems, effectively compensating for its intrinsic lack of moisture resistance through cross-linking with polysaccharides, synthetic polymers, natural particles, or active nanonetworks.

Hydroxyethyl cellulose (HEC) offers unique advantages in flexibility tuning and multicomponent compatibility. It is frequently used to construct integrated films with high strength, antimicrobial, and UV-shielding functions. An HEC/PVA/ε-polylysine composite film prepared by Zhang *et al.* (2022) achieved a maximum tensile strength of 95.9 ± 4.1 MPa and an elongation at break of 148.8 ± 2.6%, alongside translucency, efficient UV shielding, and good antimicrobial activity. Cen *et al.* (2023) investigated an HEC/carboxymethyl chitosan (CMCS)/nano-ZnO antimicrobial film, discovering that the combined effects of CMCS and ZnO reduced the film's water solubility by 94.3% and improved its UV shielding capability by 45.7%, while achieving over 99.99% inhibition against *L. monocytogenes* and *Pseudomonas aeruginosa*. Simultaneously, the elongation at break and maximum load capacity of the film were enhanced by 494% and 142%, respectively. Furthermore, Chen *et al.* (2024a) incorporated sulfated rice bran polysaccharides (SRBP) into HEC films, showing that as the SRBP content increased from 0 to 20%, the tensile strength increased from 12.66 ± 0.33 MPa to 33.04 ± 0.47 MPa, water vapor permeability decreased from 4.21×10^{-10} to 1.15×10^{-10} $g \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$, and both water solubility and moisture content were significantly reduced. Concurrently, the DPPH scavenging percentage increased to 77.83 ± 1.12%, forming distinct inhibition zones. This indicates that HEC not only can serve as a mechanical load-bearing skeleton, but it also can achieve simultaneous enhancement of mechanical strength, barrier properties, and biological activity through combination with natural polysaccharides, chitosan derivatives, and inorganic nanophases.

Hydroxypropyl methylcellulose (HPMC) and methylcellulose (MC) are commonly utilized to construct composite films with stable interfaces and controlled-release capabilities for active molecules. Cabrera-Barjas *et al.* (2025), working with an HPMC/fungal chitin nanofiber/ferulic acid system, noted that at a 5 wt% addition of chitin nanofibers, the film exhibited a tensile strength of approximately 15 MPa, plasticity of around 52%, and a water vapor permeability of 0.94×10^{-9} $g \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$; however, excessive nanofibers led to phase separation, thereby weakening tensile and barrier properties. This confirms that the reinforcing effect of nanofillers in a cellulose matrix is highly dependent on interfacial compatibility and network continuity. Dag *et al.* (2024) introduced cellulose nanofibers (CNF) and propolis-loaded zein nanoparticles into HPMC films for cheddar cheese storage, verifying that this combination could jointly improve the system's compatibility, hydrophobicity, gas barrier, and active substance release behaviors. In MC systems, Madihalli *et al.* (2025) incorporated L-arginine into methylcellulose films; the optimized film reached a tensile strength of 41.11 ± 1.03 MPa, an elongation at break of 14.11 ± 0.53%, a reduced oxygen permeability of 9.6×10^{-5} $cc \cdot m^{-1} \cdot 24\ h \cdot atm$, and a DPPH scavenging percentage of 72.28 ± 0.28%, effectively controlling weight loss and

browning when used for grape packaging for 17 days. Khater *et al.* (2023) demonstrated that incorporating AgNPs and TiO_2-NPs into HPMC substantially increased tensile strength from 39.2 to 144 MPa and 158 MPa, effectively decreased water vapor permeability. The films exhibited antimicrobial ability against *Bacillus cereus*. Moreover, Mohammadi *et al.* (2024) optimized a CMC/pectin (CMP)/chitosan nanofiber (CHNF) composite system *via* response surface methodology (optimal formulation: CMC 1.5 wt% + CMP 0.25 wt% + CHNF 0.75 wt%), where the introduction of nanofibers not only reduced the film's porosity and water vapor permeability but also significantly enhanced the system's ultimate tensile strength (UTS) and antimicrobial properties.

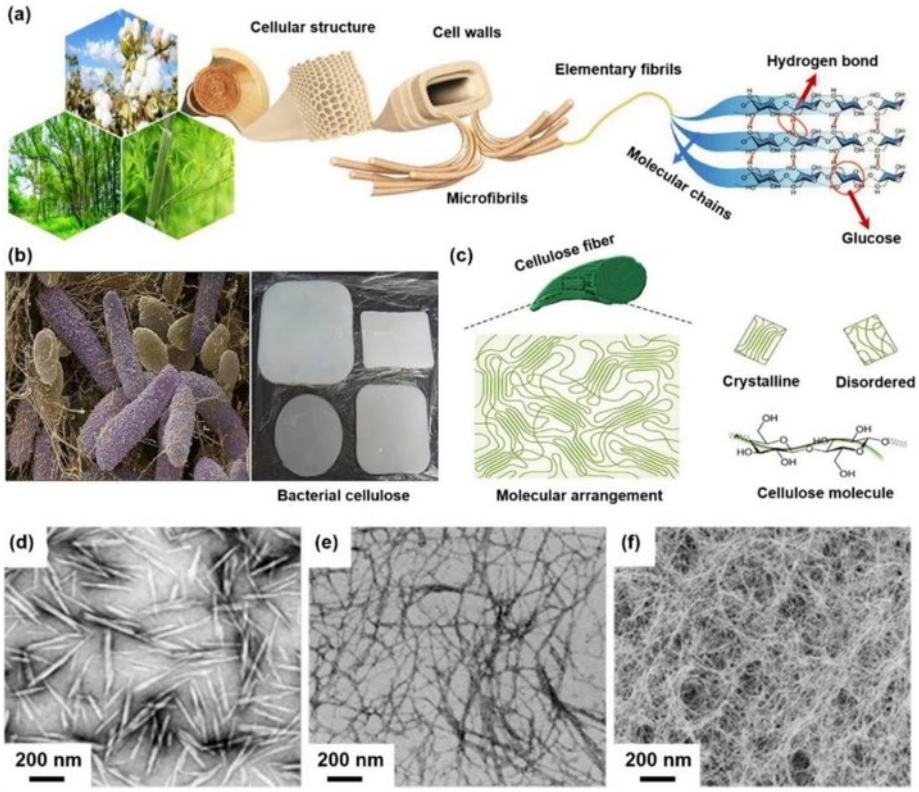

Fig. 2. Cross-scale hierarchical structure and morphological characteristics of cellulose: (a) Schematic of the hierarchical assembly of plant-derived cellulose from macroscopic tissues to molecular chains; (b) Micro-morphology and macroscopic hydrogels of bacterial cellulose; (c) Molecular arrangement configuration of crystalline and disordered regions in cellulose chains; and (d-f) Electron microscopic images of different forms of nanocellulose (*e.g.*, CNC, CNF, and bacterial cellulose networks). (Reproduced from Liu *et al.* (2022), CC BY 4.0).

When selecting material systems from sustainable sources in an attempt to achieve high intrinsic mechanical properties, regenerated cellulose, cellulose-lignin films, and nanocellulose films present enormous potential. Cellulose-lignin composite films developed by He *et al.* (2023) maintained a high tensile strength of 75.9 MPa even at a lignin content of up to 30%. When combined with 3% ε-polylysine, the bactericidal percentage approached 100%, demonstrating excellent UV shielding, hydrophobicity, and water/oxygen barrier performance. Concurrently, Han *et al.* (2024) also validated the broad application prospects of all-cellulose composites in the development of antimicrobial and degradable active packaging. Qi *et al.* (2025) prepared grape preservation films using wheat straw-derived CMC, glycerol, and polymalate, achieving a tensile strength of 28.4

MPa, an elongation at break of 142.1%, and a water vapor permeability as low as 0.55 × 10^{-12} g·m/(m²·s·Pa), effectively maintaining the storage quality of grapes. Paudel *et al.* (2025) utilized grapevine waste to extract cellulose for preparing transparent films, which achieved a transmittance of 83.7% to 84.30% mm^{-1}, a tensile strength of 15.4 to 18.2 MPa, and complete degradation in soil within 17 days. Furthermore, Lovely *et al.* (2025) optimized CNF films *via* a low-pressure homogenization process, showing that homogenization reduced the oxygen transmission from 0.48 to 0.25 cc·μm/(m²·day·kPa) (at 50% RH), increased tensile strength from 94 to 157 MPa, raised Young's modulus from 2630 to 3840 MPa, lowered surface roughness (S_a) from 4.73 to 2.64 μm, and maintained crystallinity at approximately 64%. These studies collectively indicate that the "structural refinement" processing technique itself can significantly enhance the strength and oxygen barrier properties of cellulose materials, making them highly suitable as high-performance load-bearing skeletons for active packaging.

In summary, current representative studies indicate that, compared to starch, cellulose and its derivatives have more prominent mechanical support and oxygen barrier potential. Their tensile strength typically ranges from 12–15 MPa to 60–95 MPa, reaching up to 157 MPa in highly dense nanocellulose films. Concurrently, by compounding with lignin, polyphenols, polysaccharides, ε-polylysine, inorganic nanoparticles, or carbon dots, their antioxidant, antimicrobial, and UV-shielding functions can be significantly enhanced. However, such systems are generally constrained by inherent hydrophilicity and limited water vapor barrier capacity. Therefore, in high-humidity environments and long-cycle supply chain scenarios, cellulose-based composite films are more suitable as mechanical support layers, oxygen barrier layers, or functionally active layers in multilayer packaging structures, rather than independently bearing the sole responsibility of moisture protection. In short, the core application value of cellulose and its derivatives lies not in simply replacing traditional plastics, but in providing a skeletal platform that combines high mechanical support, sustainability, and multifunctional potential for degradable active packaging.

Chitosan matrices

Chitosan (CS) is one of the materials with potential for "active packaging" applications among natural polysaccharide matrices. Compared to starch and most cellulose derivatives, the chitosan macromolecular skeleton contains a large number of protonatable primary amino groups. This chemical structure provides the system with film-forming properties and intrinsic antibacterial ability, while also exhibiting certain oxygen barrier potential and interfacial reactivity. Chitosan can be directly used as a food contact layer or as a carrier for active molecules, polyphenols, nanoparticles, and polysaccharide reinforcing phases. However, the chitosan matrix has physical limitations such as relatively strong hydrophilicity, susceptibility to swelling in wet states, insufficient long-term water resistance stability, and relatively high brittleness of pure films. Therefore, recent research has primarily focused on balancing its structural stability and active functions through strategies such as chemical cross-linking, nanocompositing, the introduction of plant extracts, and the construction of edible coatings.

In terms of structural modification, cross-linking and the introduction of natural phenolic substances are commonly used strategies. Westlake *et al.* (2023a) utilized vanillin-cross-linked chitosan to construct active packaging films loaded with green tea polyphenols. As shown in Fig. 3, the formation of the Schiff base cross-linked network reduced the water solubility and moisture content of the system, achieved a tensile strength

of 20.9 ± 3 MPa, and altered the release kinetics of the polyphenols. In food simulants (Fig. 3A), green tea polyphenols exhibited burst release characteristics within the initial 8 h (releasing approximately 70%), followed by a steady release phase lasting up to 400 h. Electron microscopic images (Fig. 3B) showed the gradual formation of microscopic diffusion channels in the film cross-section over immersion time, indicating a matrix network-mediated Fickian diffusion mechanism. The film also demonstrated a 100% UV shielding rate. Experimental data demonstrate that altering the polymer network structure *via* covalent cross-linking allows for the quantitative regulation of the active molecule's release cycle. Hu *et al.* (2022) introduced persimmon peel extract (PPE) into chitosan films. When the PPE addition was 10%, the water vapor permeability (WVP) of the film decreased from 5.78 ± 0.23 × 10^{-3} g·mm/(m^2·s·Pa) for the pure film to 3.12 ± 0.04 × 10^{-3} g·mm/(m^2·s·Pa). The DPPH scavenging rate increased from 11.82 ± 1.02% to 73.43 ± 3.29%. In banana preservation tests, the weight loss rate of the CS-PPE 10 packaging group at the end of storage was 4.78%, which was lower than the 8.98% of the unpackaged group. Hamed *et al.* (2024) added 4% purified *Moringa oleifera* flavonoids to chitosan films, decreasing the WVP from 8.85 to 2.47 g·mm/(m^2·s·Pa), increasing mechanical properties and antioxidant activity, and inhibiting the proliferation of pathogenic bacteria in hamburger meat. Studies indicate that constructing hydrogen bonds or Schiff base networks *via* aromatic aldehydes, polyphenols, and plant flavonoids can improve the gas/moisture barrier properties and service-life stability of chitosan films.

In composite system design, chitosan exhibits structural compatibility with various reinforcing phases. Subramani and Manian (2024) introduced bio-based vanillin and kaolin into chitosan films, increasing the DPPH free radical scavenging percentage from 55.6% (pure film) to 80%, with an inhibition of approximately 90% against *Escherichia coli* and *Staphylococcus aureus*. Souza *et al.* (2021) investigated the mechanical effect of ZnO nanoparticles (NPs) on chitosan films. After adding 0.5%, 1.0%, and 2.0% ZnO NPs, the tensile strength of the system (46.7 MPa for the pure film) was decreased by 30.8%, 22.5%, and 34.9%, respectively. This result indicates that ZnO NPs synthesized from food by-products acted as a toughening and plasticizing agent in this system, transitioning the material from brittleness to ductility while maintaining gas barrier properties. To reduce the degree of swelling under high-humidity conditions, Zhao *et al.* (2025a) constructed a CS-CNF/VA25-Ca1.5 multiple cross-linked film. This system remained intact after immersion in room-temperature water for over 32 days and did not disintegrate in 60 °C water for 24 h (pure chitosan film dissolved completely within 3 min); its oxygen permeability was 0.9 cm^3·μm/(m^2·d·kPa), the DPPH scavenging percentage was 93.6%, and the shelf life of strawberries at room temperature was extended to 7 days. This demonstrates that multiple cross-linking and nanocomposites can effectively inhibit the rapid swelling of the film layer. Deep-eutectic-solvent-assisted pullulan/carboxymethyl-chitosan films containing zein–nisin nanofillers also showed improved physicomechanical and antimicrobial performance (Ashraf *et al.* 2026b).

The chitosan matrix is also widely applied in edible coatings and fruit/vegetable preservation research. Yan *et al.* (2024) introduced *trans*-cinnamaldehyde essential oil into a chitosan/diepoxy-poly(ethylene glycol) system. The prepared cross-linked coating exhibited changes in tensile properties, light transmittance, water vapor barrier, and antibacterial properties; in banana storage applications, the coating reduced the respiration rate and weight loss rate of the fruit, extending the preservation period to 24 days. A chitosan/ascorbic acid/curcumin composite coating (CS-AA-Cur 20) constructed by Zhou *et al.* (2025) reduced the weight loss rate, decay rate, and accumulation of malondialdehyde

(MDA) and H_2O_2 in strawberries refrigerated at 4 °C, extending the shelf life to 15 days. Soni *et al.* (2025) used an *Ocimum gratissimum* essential oil nanoemulsion to construct a chitosan coating. The coating showed minimum inhibitory concentrations (MIC) against five tested fungi ranging from 0.05 to 0.25 μL/mL. In room-temperature strawberry preservation experiments, the weight loss rate of the treated group was reduced by 49.7%, and the basic quality of the fruit was maintained for 8 days. Test results indicate that chitosan can act as a matrix carrier to be compounded with antioxidants and essential oils to regulate moisture volatilization and microbial activity on the surface of fruits and vegetables.

For meat and poultry food preservation, the chitosan matrix is frequently used as a release layer for antibacterial and antioxidant components. Shiryanpour *et al.* (2025) loaded essential oil and anthocyanin in the form of a double nanoemulsion (DNE) into chitosan films for chicken breast preservation. After 16 days, the pH value (6.23), total volatile basic nitrogen (18.5 mg N/100 g), and total viable count (4.6 log CFU/g) of the DNE-treated group were lower than those of the control group (6.85, 31.2 mg N/100 g, and 7.8 log CFU/g, respectively), extending the shelf life within the test period. Tan *et al.* (2025) introduced caffeic acid-grafted inulin into chitosan films, observing increases in tensile strength, elongation at break, UV shielding capability, and antibacterial performance, and a reduction in the decay rate of tested strawberries. In composite systems containing metal nanoparticles, Deb *et al.* (2025) introduced Indian gooseberry extract and silver nanoparticles (AgNPs) into chitosan films. The tensile strength increased from 29.29 ± 1.04 MPa for the pure film to 46.62 ± 0.82 MPa, and the elongation at break increased from 36.21 ± 1.87% to 89.39 ± 1.11%; water absorption, water vapor transmission rate (decreased to 313.94 ± 1.81 g/m²/day), and water solubility all exhibited downward trends. Degradation tests showed that the pure chitosan film lost approximately 93.0% of its mass in the first 3 weeks, whereas the composite film lost 34.8% of its mass in the first month, reaching 93.4% by the end of the second month. This illustrates that the composite of inorganic nanoparticles and cross-linked networks can alter the service-life and degradation kinetics of the material.

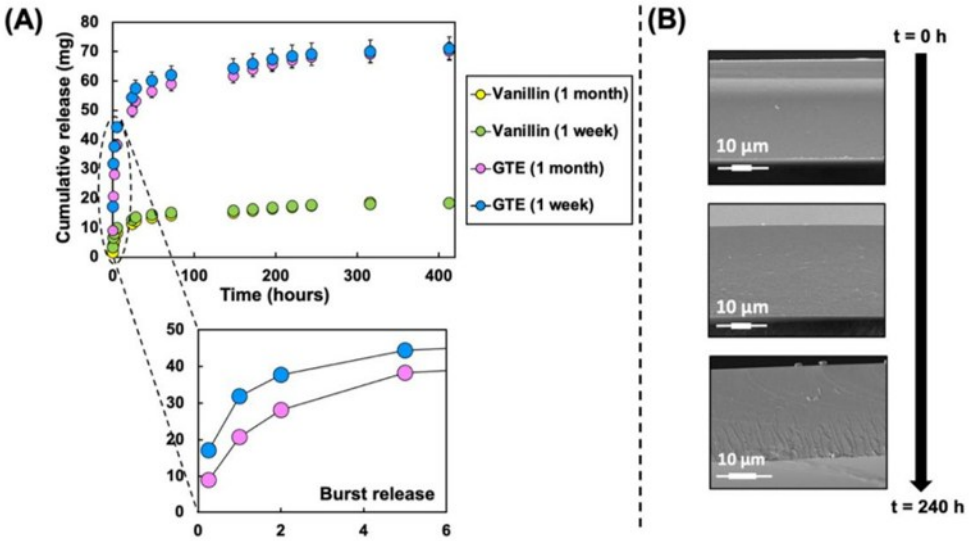

Fig. 3. (A) Cumulative release profiles of green tea polyphenols from vanillin cross-linked chitosan films (inset shows the initial burst release phase); (B) Microstructural evolution of the film cross-section during the release process (t = 0 to t = 240 h). (Reproduced from Westlake *et al.* (2023a), CC BY 4.0).

In summary, recent experimental data indicate that chitosan has potential for application in active contact layers, edible coatings, and barrier functional layers. Its structural optimization primarily focuses on: (1) utilizing vanillin, cinnamaldehyde, *etc*., to construct cross-linked networks to improve mechanical stability and water resistance; (2) introducing polyphenols, flavonoids, essential oils, and plant extracts to increase antioxidant and antibacterial activity; (3) utilizing nanoparticles and emulsion systems to construct controlled-release networks for active substances. Its primary physical limitation remains its swelling behavior under high-humidity conditions. In practical packaging structure design, chitosan is frequently used as an inner layer or functional coating, undergoing multilayer compounding with starch, cellulose, protein, or biodegradable polyester materials.

Alginate and pectin matrices

Before discussing the composite modification strategies for use in packaging materials, it is necessary to briefly outline the molecular structural characteristics and intrinsic gelation mechanisms of alginate and pectin. Alginate, which is primarily extracted from natural brown algae, is a linear anionic polysaccharide copolymerized by (1→4)-linked β-D-mannuronic acid (M units) and α-L-guluronic acid (G units) in various sequences (M-blocks, G-blocks, and alternating MG-blocks). Its core mechanism for film formation and crosslinking lies in the specific coordination and chelation of divalent cations (*e.g.*, Ca^{2+}, Fe^{2+}) with the G-blocks on adjacent polymer chains, forming the classic three-dimensional "egg-box" gel network. Pectin, widely present in the primary cell walls and middle lamella of higher plants, features a structural backbone primarily composed of a homogalacturonan chain of α-(1→4)-linked D-galacturonic acid. Based on the degree of esterification (DE) of its carboxyl groups, pectin is generally classified into high-methoxyl pectin (HMP, DE > 50%) and low-methoxyl pectin (LMP, DE < 50%). The gelation mechanism of LMP is highly similar to that of alginate, as it can also form the "egg-box" conformation through the interaction between free carboxyl groups and divalent cations. This characteristic molecular structure based on uronic acid residues and the capability for metal ion coordination constitute the underlying chemical foundation for these two polysaccharides to undergo liquid-solid phase transitions and form edible interfaces under mild conditions.

Building upon these structural properties, alginate and pectin, as typical natural anionic polysaccharide matrices, exhibit macroscopic material characteristics such as broad availability, edibility, biodegradability, and relatively high transparency. Compared to starch and chitosan, their primary advantages in the field of active packaging include mild film-forming conditions, facile ionic crosslinking, and excellent physicochemical compatibility with polyphenols, essential oils, and plant extracts. However, because their polysaccharide backbones are rich in hydroxyl and free carboxyl groups, the materials themselves are highly hydrophilic. In environments with high relative humidity, they are prone to water absorption and plasticization, leading to a severe decline in mechanical strength and water vapor barrier performance. Addressing these intrinsic shortcomings, recent research has focused on establishing a more stable balance among structural integrity, barrier properties, and the release kinetics of active agents through ionic crosslinking, compounding with plant extracts, second-phase reinforcement, and dual-network structural design.

In alginate systems, incorporating natural by-products or essential oils to fabricate active composite films is an effective strategy for enhancing overall material performance.

Khwaldia *et al.* (2023) introduced date palm pit extract (DPPE) into an alginate matrix, demonstrating that the addition of 10% DPPE significantly improved the water vapor barrier properties of the films, while increasing the tensile strength (TS) and elongation at break (EAB) by over 50% and 45%, respectively; simultaneously, the water solubility of the films decreased by 37% to 64%, and the surface wettability was reduced by 72% to 111%. This indicates that polyphenol-rich plant by-products not only impart antioxidant activity to the matrix but also effectively mitigate the polarity and water absorption of alginate (Khwaldia *et al.* 2023). Yun and Liu (2024) further directly incorporated 12 varieties of mandarin peel powder into sodium alginate films. The resulting composite films exhibited thicknesses of 118 to 152 μm, moisture contents of 16.4% to 23.6%, water contact angles of 26.0° to 90.8°, WVPs of 5.38 to 8.31 × 10^{-11} g·m^{-1}·s^{-1}·Pa^{-1}, oxygen permeabilities of 5.26 to 12.91 × 10^{-20} m^2·s^{-1}·Pa^{-1}, TS values of 4.87 to 7.90 MPa, and EAB values of 13.4% to 24.6%. Microstructural analysis revealed that higher pectin and lipid contents in the mandarin peels facilitated the formation of a dense matrix, whereas excessive crude fiber content tended to induce internal microcracks, thereby compromising the mechanical and barrier properties. These data confirm that the performance of composite films depends not merely on the loading amount of the active agents, but is highly reliant on the compatibility and spatial arrangement of the second-phase components within the polysaccharide network.

The combined use of ionic crosslinking and ultrasonic emulsification is another critical pathway for optimizing the performance of alginate-based packaging. Asmadi *et al.* (2025) prepared active sodium alginate films by combining sonication, internal crosslinking with 2% $CaCl_2$, and the incorporation of 1% patchouli essential oil (PEO). The optimal formulation (S5/C2/PEO) achieved a TS of 31.8 MPa, a WVP reduced to 2.11 × 10^{-11} g·m^{-1}·h^{-1}·Pa^{-1}, and exhibited excellent thermal stability. In storage trials with cherry tomatoes, this packaging significantly inhibited mold growth over 4 d. Wardak *et al.* (2024) loaded kiwifruit seed essential oil (KSO) into sodium alginate coatings and found that the KSO30 formulation possessed an excellent combination of structural integrity, hydrophobicity, barrier, and mechanical properties. When applied to persimmon preservation, the KSO30-treated group showed a weight loss of only 5.1% at the end of storage (compared to 6.8% for the control) and a pH of 6.3 (compared to 6.1 for the control), effectively delaying the loss of fruit firmness and the onset of the respiratory peak. Furthermore, the SA/QKC (sodium alginate (SA) with quaternary ammonium lignin-cinnamaldehyde (QKC) composite) antibacterial coatings developed by Miao *et al.* (2025) demonstrated that with 5 wt% QKC, the TS of the sodium alginate coating increased from 11.5 to 24.4 MPa, and the WVP decreased by 35.4%. The inhibition percentages against *Staphylococcus aureus* (*S. aureus*) and *Escherichia coli* (*E. coli*) reached 96% and 65%, respectively, effectively reducing weight loss and decay in persimmons and citrus fruits during storage. These studies indicate that through crosslinking and emulsification-dispersion technologies, alginate can be efficiently transformed into an active physical barrier with tunable functions.

Beyond serving as physical barriers, the multiscale structural design of alginate matrices facilitates the integration of smart indicating and advanced active functionalities. As illustrated in Fig. 4, recent modifications emphasize environmentally friendly chemical grafting and the incorporation of nanocarriers. Zhang *et al.* (2024b) developed a polyvinyl alcohol/sodium alginate (PVA/SA) composite film loaded with ZIF-8-alizarin (PVA-SA-ZA). The alginate backbone was covalently grafted with 4-phenylsemicarbazide and subsequently crosslinked *via* Ca^{2+} to stably anchor the MOF nanocarriers (Fig. 4a). During

refrigerated beef storage, the film's color difference exhibited a linear correlation with total volatile basic nitrogen (TVB-N) concentrations, providing visual feedback for ammonia release (Figs. 4b, 4c). In the realm of active preservation, incorporating Pickering emulsions and multilayer networks further enhances the physical isolation capacity of alginate. For instance, incorporating a baobab seed oil pickering emulsion (BOPE) into an alginate/guar gum matrix restricted cross-interfacial moisture migration and delayed epidermal browning in *Agaricus bisporus* mushrooms over 30 d (Fig. 4d) (Yang *et al.* 2024a). Similarly, bilayer composite films incorporating TiO_2 NPs effectively inhibited mold proliferation across various temperature gradients of 4 °C, 10 °C, and 25 °C (Fig. 4e) (Yang *et al.* 2024b). These results demonstrate that combining molecular-level modification with nanocarrier blending allows alginate matrices to simultaneously achieve environmental responsiveness and long-term microbial inhibition.

In contrast, the physicochemical behavior of pectin-based materials exhibits a prominent coupling characteristic of "source variance–structural variance–performance variance". Jiang *et al.* (2023a) systematically evaluated the film-forming properties of pectin extracted from pomelo, lemon, and white-fleshed pitaya peels. The results showed that the WVPs of the three pectin films were 1.67 ± 0.30, 1.63 ± 1.35, and 1.65 ± 1.06 × 10^{-9} g·m^{-1}·s^{-1}·Pa^{-1}, respectively; their TS values were 22.25 ± 1.52, 31.26 ± 2.30, and 32.40 ± 1.65 MPa, respectively, with the white-fleshed pitaya peel pectin film exhibiting the highest EAB (10.95 ± 1.51%). Such significant macroscopic differences in mechanics and barrier properties are primarily attributed to the source-dependent heterogeneity in monosaccharide composition, DE, and crystallinity. This implies that in practical packaging applications, the selection of a pectin matrix must be specifically matched according to its botanical origin and extraction process.

For pectin-based active packaging, essential oil encapsulation and functionalization with natural polyphenols are the core strategies to enhance material activity. Pectin films loaded with lemon essential oil microcapsules, reported by Akachat *et al.* (2025), showed that the incorporation of the essential oil increased the EAB from 11.52 ± 0.12% to 20.05 ± 0.78%, improved the TS from 12.28 ± 1.27 MPa to 14.68 ± 1.42 MPa, and surged the DPPH radical scavenging percentage from 21.37 ± 0.001% to 63.60 ± 0.001%. Morphological analysis indicated that essential oil loading transitioned the film surface from a smooth state to a rough topography containing spherical structures and interconnected channels, reflecting the structural reconfiguration of the hydrophobic phase within the hydrophilic pectin network. The apple pectin–ε-polylysine–luteolin (APPL-Lu) composite coating developed by Li *et al.* (2026) further verified the combined effects of multiple components. The addition of luteolin significantly increased the water contact angle of the films from 66.9° (pure AP) and 60.5° (APPL) to 118.0°, achieving effective surface hydrophobic modification. Mechanical testing revealed that at a luteolin concentration of 0.15%, the EAB was increased to 38.6%, which was 90.1% and 40.4% higher than those of the AP and APPL films, respectively. In fresh-cut apple preservation tests, the APPL-Lu treated group maintained a firmness of 10.7 N at the end of storage (a mere 6.2% decrease from the initial value, and 41.5% higher than the control group), with a weight loss of only 0.12% (compared to 1.5% for the control). This series of studies confirmed that the molecular-level combined action of antimicrobial peptides and natural polyphenols can endow pectin coatings with excellent interfacial adhesion, hydrophobicity, and antidegration efficacy.

For dual-component composite systems of pectin and alginate, constructing dual-network and multiple-crosslinking structures is a critical approach to overcoming the

bottleneck of intrinsic hydration sensitivity. He *et al.* (2024) fabricated pectin/sodium alginate (PS) composite films by introducing tannic acid (TA) and Fe^{3+} to build metal-phenol networks. The study found that this coordination network increased the film thickness from 45.00 ± 3.53 μm to 63.89 ± 3.66 μm (with TA) and 67.63 ± 3.07 μm (with TA-Fe^{3+}), reduced water permeability by 59.8% and bestowed the material with superior UV-blocking capabilities and a denser crosslinked microstructure. When applied as a coating for golden passion fruit, this composite film significantly reduced the fruit's water loss rate and maintained its freshness. Hoque *et al.* (2024) further investigated the reinforcement mechanism of microcrystalline cellulose (MCC) and geraniol in PEC/SA composite systems. In a system crosslinked with 2.0% $CaCl_2$, the addition of 10% MCC significantly enhanced the TS of the films; with the subsequent incorporation of geraniol at various concentrations (2.5%, 5.0%, 7.5%, 10.0%), the water solubility of the composite films notably decreased, water vapor and oxygen barrier properties were substantially strengthened, and complete inhibition of *E. coli* and *Bacillus cereus* was achieved within 24 h. Thermogravimetric analysis (TGA) demonstrated that the blending of MCC and geraniol increased the onset thermal decomposition temperature of the system from 195 °C to 221 °C, and elevated the temperature of the maximum thermal degradation rate (T_{max}) from 237 to 260 °C. This evolutionary process demonstrates that through the multidimensional integration of ionic crosslinking, metal-phenol networks, and cellulose reinforcing phases, highly hydrophilic and easily plasticized anionic natural polysaccharides can be effectively transformed into advanced packaging interfaces with high mechanical integrity and active protective functions.

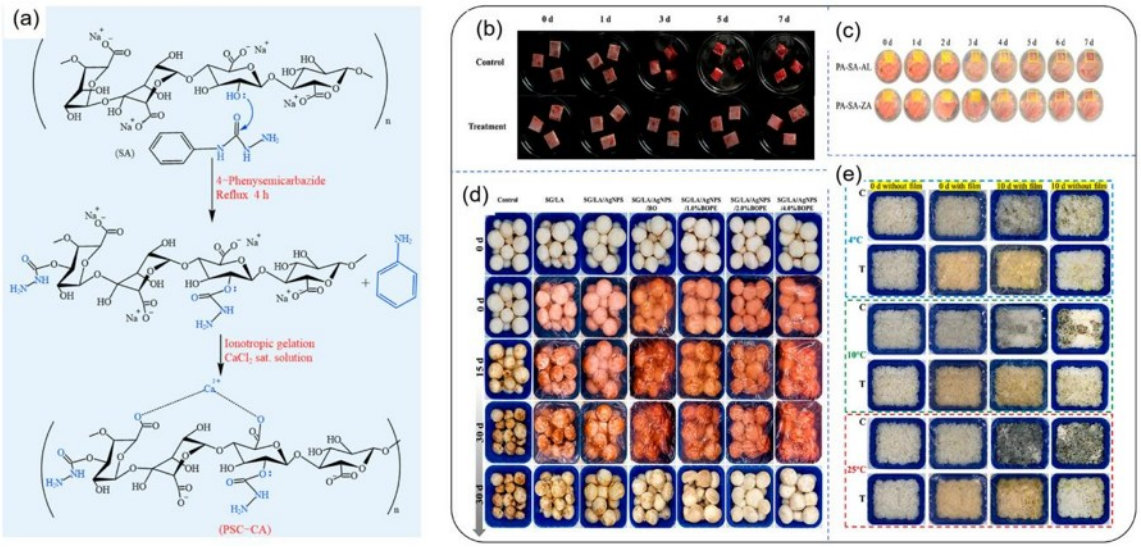

Fig. 4. Modification mechanisms and comprehensive applications of sodium alginate-based packaging materials: (a) Schematic representation of the chemical grafting and Ca^{2+} cross-linking mechanism; (b, c) Colorimetric response of PA-SA-ZA smart indicator films during beef refrigeration; (d) Preservation effect of BOPE-incorporated composite films on *Agaricus bisporus* mushrooms; and (e) Inhibition of target spoilage by composite films under different temperatures. Adapted from Wang *et al.* (2025e), Figs. 12 and 17, under CC BY 4.0.

In summary, within the realm of natural biopolymer systems, alginate and pectin are positioned as anionic polysaccharide platforms characterized by mild film-forming conditions, facile crosslinkability, and high functionalization potential. Alginate, relying

on Ca^{2+}/Fe^{3+} ion coordination to rapidly form stable networks, holds immense engineering application potential for fresh produce preservation coatings and edible active packaging layers; pectin, owing to its excellent matrix dispersibility, is more suitable as a carrier substrate for polyphenols, essential oils, and antimicrobial peptides. Addressing their mutual plasticization issues in high-humidity environments, a more promising future research paradigm should not be limited to the simple substitution of traditional plastics. Instead, it should focus on multilayer composite technologies incorporating nanocellulose, proteins, lipid phases, or biodegradable polyesters, enabling the polysaccharide matrices to precisely assume specific roles in structural support, functional release control, or interfacial regulation within complex packaging architectures.

Protein-based matrices

Compared to polysaccharide systems, the molecular chains of protein-based matrices contain amino, carboxyl, hydroxyl, and sulfur-containing groups, allowing for network reconfiguration through chemical or physical methods such as heat-induced denaturation, enzymatic cross-linking, metal-polyphenol coordination, Schiff base reactions, and pH-driven self-assembly. This structural characteristic endows protein matrices with film-forming, active substance-loading, and interfacial adhesion capabilities, making them frequently applied in packaging systems for meat, seafood, and fresh-cut fruits and vegetables. However, natural protein films exhibit physical limitations such as high moisture sensitivity, limited water vapor barrier capacity, and narrow processing windows. Recent research has primarily focused on compounding proteins with polysaccharides, nanofillers, hydrophobic active agents, or smart indicator components to construct multiscale cross-linked networks, thereby regulating the mechanical properties, barrier capacities, and release kinetics of active substances.

Animal-derived proteins: Gelatin and whey protein

Among animal-derived proteins, gelatin and whey protein are commonly used film matrices in active packaging. Gelatin possesses good film-forming properties and transparency, and exhibits structural compatibility with meat surfaces, making it suitable for constructing adherent active films or coatings. Experiments have demonstrated that compounding gelatin with hydrophobic proteins, essential oil carriers, or nanoparticles alters its hygroscopicity and controlled-release behavior. Wu *et al.* (2023) developed an electrospun gelatin/zein nanofiber film co-loaded with cinnamaldehyde and thymol for strawberry packaging. The film showed improved hydrophobicity and barrier performance, with a water contact angle of 85.1° and a water vapor transmission rate of 3.1×10^{-8} $g \cdot mm^{-1} \cdot h^{-1} \cdot Pa^{-1}$. It also retained good mechanical properties, with a tensile strength of 1.30 MPa and an EAB of 185%. Hong *et al.* (2024) introduced cinnamon essential oil-loaded metal-organic frameworks (MOFs) into a gelatin/pullulan composite film; in meat preservation tests, the inhibition approached 99.9%, and the pH variation and weight loss of the samples were mitigated. Xu *et al.* (2025a) reinforced gelatin films with zein-quercetin NPs, resulting in a composite film with a tensile strength of approximately 3.2 MPa, an EAB of about 142%, water vapor and oxygen transmission rates decreased by 78.4% and 76.9%, respectively, a water contact angle of 112.0 ± 0.6°, and a DPPH radical scavenging rate of 64.9 ± 0.7%. Khan *et al.* (2023) incorporated green tea carbon dots into a chitosan/gelatin system for pork preservation, similarly validating the loading capacity of the gelatin network for natural antioxidant factors.

Constructing active delivery networks *via* emulsion or vesicle structures is another pathway for gelatin modification. A Schiff-base-crosslinked β-cyclodextrin/gelatin–carrageenan film has been found to enable controlled carvacrol release for ready-to-eat food preservation (Cui *et al.* 2023). Ran *et al.* (2024) introduced doubly stabilized clove essential oil chitosomes into gelatin/polyvinyl alcohol (PVA) films; the addition of composite nanoparticles reduced the swelling index of the films from 964% to 495%, regulated the release rate of the essential oil, and extended the shelf life of marinated steaks from 3 days to 7 days. Acharya *et al.* (2025) designed a Pickering emulsion-based pH-responsive gelatin film, utilizing bacterial cellulose nanocrystal-nanochitosan (BCNC-nCS) composite particles to stabilize the emulsion and load black pepper essential oil for duck meat preservation. The study demonstrated that the gelatin network can achieve targeted release triggered by environmental pH *via* emulsion microstructures. Lima *et al.* (2025) introduced tea tree essential oil into gelatin-based packaging, which produced inhibition zones of 17 mm and 9 mm against *Pseudomonas aeruginosa* and *Salmonella enterica*, respectively, with an established minimum inhibitory concentration (MIC) range of 10% to 15%.

Whey protein isolate (WPI) possesses intrinsic oxygen and lipid barrier properties due to its intramolecular disulfide bonds and conformational characteristics. Dai *et al.* (2024) loaded chlorogenic acid into a sweet whey/starch composite film; the UV shielding rate at 315 nm was increased by 54.6%, the inhibition rate against *E. coli* increased by 47.5%, and the ABTS scavenging rate improved by 74.5%. Gao *et al.* (2024) analyzed the release kinetics of cinnamaldehyde in whey protein/HPMC films, showing that its release behavior was adequately described by the Fickian power-law and Weibull models. In smart indicator systems, Kiani-Salmi *et al.* (2025) constructed a chitosan/WPI/betacyanin/carbon dot composite film with inhibition zones of 20 ± 1.2 mm and 15 ± 0.36 mm against *S. aureus* and *E. coli*, respectively. The TS ranged from 79.4 to 91.7 MPa, and the WVP decreased from 6.90×10^{-11} to 2.54×10^{-11} g·m/(m²·s·Pa). Using chitosan and transglutaminase-modified whey protein as film-forming substrates, Liu *et al.* (2025c) prepared UV-resistant alizarin/curcumin-based pH indicator films for shrimp freshness monitoring, demonstrating that enzymatic cross-linking alters the water resistance and mechanical stability of the whey protein network. Leaching-resistant anthocyanin bigels and chitosan–quercetin films have also been used for colorimetric monitoring of volatile amines and fish spoilage, respectively (Zhai *et al.* 2022; Wu *et al.* 2025). Together, these studies indicate that WPI-based composite networks can integrate barrier and antimicrobial functions with colorimetric freshness monitoring. The reliability of the sensing response is closely related to the stability of the pigment within the polymer microenvironment. Betacyanins, alizarin, and curcumin may undergo light-, oxygen-, temperature-, or moisture-induced changes during storage, while film thickness, pigment distribution, polymer–pigment interactions, and headspace humidity can alter the initial color and response range. Consequently, color responses obtained in buffer solutions or model headspaces need to be correlated with food-specific spoilage indices, such as pH, total volatile basic nitrogen, microbial counts, or biogenic amine concentrations, under realistic storage conditions. Response time, instrumental color difference, repeatability, and pre-use storage stability are therefore important parameters for evaluating sensing accuracy. At the package level, indicator migration, batch-to-batch variation in natural pigments, standardized visual or smartphone-based color acquisition, and compatibility with scalable coating or printing processes will further determine the transition of these systems from

laboratory prototypes to practical packaging applications (Stoica *et al.* 2024; Yang *et al.* 2025a).

Plant-derived proteins: Zein and soy protein

In the domain of plant-derived proteins, zein and soy protein isolate (SPI) are two primary film matrices. Zein possesses high surface hydrophobicity and is frequently utilized as a carrier for lipid-soluble essential oils and hydrophobic antimicrobial agents. SPI features numerous side-chain reactive sites, making it suitable for network cross-linking *via* chemical or physical modifications. Research on zein has primarily focused on the construction of electrospun nanofiber mats and nanocomposite films. A zein film containing pomegranate-peel-extract-loaded chitosan nanoparticles achieved sustained active release with inhibition of *L. monocytogenes* in pork (Cui *et al.* 2020). Khalil *et al.* (2024) prepared zein electrospun mats loaded with nisin to control *Listeria monocytogenes* on peach surfaces, testing the sustained release behavior of the nanofibers. Gholizadeh *et al.* (2024) introduced geraniol nanoliposomes into zein nanofiber mats, achieving the encapsulation and release of hydrophobic active substances. Yi *et al.* (2024) and Zhang *et al.* (2025b) constructed active zein films utilizing gallic acid-loaded γ-CD-MOFs and composite AgNPs, respectively. Zhang *et al.* (2025b) reported that the composite film exhibited inhibition rates of 44.6% to 78.0% and 28.4% to 59.5% against *E. coli* O157:H7 and *Salmonella enterica*, respectively, maintained antioxidant activity for approximately 100 days, and extended the shelf life of refrigerated pork by 9 days.

Cross-linking modifications can alter the mechanical and barrier properties of zein systems. Wei *et al.* (2025a) applied citric acid vapor-assisted cross-linking to nisin-embedded zein/PEG composite nanofiber membranes. The film exhibited a water vapor transmission rate of 150.47 ± 7.14 $g \cdot m^{-2} \cdot 24\ h^{-1}$, an oxygen transmission rate of 59.74 ± 3.10 $cm^3 \cdot m^{-2} \cdot 24\ h^{-1}$, and inhibition zones of 11.52 ± 0.44 mm and 10.67 ± 0.46 mm against *E. coli* and *S. aureus*, respectively. After 10 days of cooled goose meat preservation, the pH, TVB-N, and total viable count (TVC) of the samples were approximately 5.7, 11.3 mg/100 g, and 5.01 ± 0.69 log CFU/g, respectively. Kazemi *et al.* (2026) noted that under specific concentration, voltage, and flow rate conditions, the zein spinning system produced an inhibition zone of 12.2 mm against *L. monocytogenes* and retained approximately 38.2% of its DPPH scavenging ability. Cheng *et al.* (2024) confirmed that the addition of TiO_2 nanotube arrays also altered the mechanical strength and structural compactness of zein films.

SPI research has emphasized the construction of covalent or non-covalent cross-linked networks. Sun *et al.* (2024) introduced a starch aldehyde–quercetin conjugate into SPI; the resulting films achieved DPPH and ABTS scavenging percentages of 79.8% and 62.1%, respectively, alongside changes in light shielding, thermal stability, and surface hydrophobicity. Choo *et al.* (2024) incorporated phage CAM-21 into SPI films; the phage remained active under pH 3 to 11 and 55 °C conditions and inhibited *E. coli* O157:H7 in beef test groups. Ren *et al.* (2024) added 10% tara pod extract to SPI films, increasing tensile strength by 56.4%; after 90 days of beef tallow packaging, the peroxide value was 0.002 g/100 g (compared to 0.0835 g/100 g for the polyethylene control film).

In constructing multiphase structures to regulate the release of volatile active substances, the introduction of high internal phase (HIP) emulsions provides a novel interfacial design strategy for SPI films. Zhao *et al.* (2024b) prepared an oil-in-water (O/W) HIP emulsion and incorporated it into an SPI film-forming solution to load thymol. As illustrated in Fig. 5, confocal laser scanning microscope (CLSM) images demonstrated that

within the HIP emulsion system, oil droplets were smaller and more uniformly distributed within the film-forming solution and the final films (Figs. 5a, 5b), reducing the migration degree of the oil droplets. Physicochemical analyses revealed (Fig. 5c) that the HIP emulsion films containing 30% oil phase exhibited the lowest WVP (1.15×10^{-10} $g \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$), glass transition temperature (40.9 °C), and TS (4.47 MPa), alongside the highest transparency value (12.9) and EAB (161%). Further antimicrobial tests demonstrated that, compared to conventional O/W emulsion or pure oil systems, the HIP-based SPI films exhibited a higher thymol encapsulation efficiency (Fig. 5d) and more pronounced sustained-release characteristics, thereby achieving more prolonged growth inhibition against the tested microbes. This study confirmed the regulatory role of high internal phase emulsions on the mechanical flexibility of the SPI matrix and the controlled release of hydrophobic active molecules.

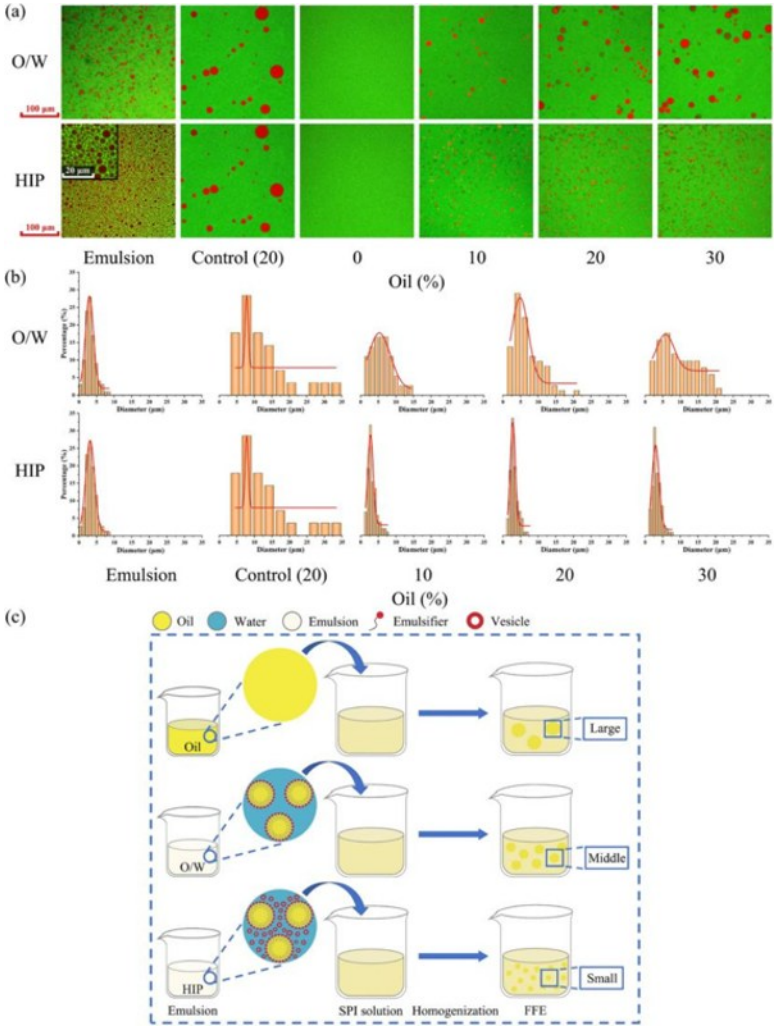

Fig. 5. Micro-morphology and physicochemical properties of SPI films modified by high internal phase (HIP) emulsions loaded with thymol: (a) Confocal laser scanning microscope (CLSM) images of conventional oil-in-water (O/W) emulsions and HIP emulsions in film-forming solutions and films; (b) Particle size distribution curves of the oil droplets; (c) Schematic illustrating the formation of SPI films with varying oil droplet distribution characteristics; (d) Comparison of thymol encapsulation efficiency among the SPI-based emulsion films. (Zhao *et al.* (2024b), CC BY-NC 4.0).

In fruit and vegetable preservation applications, Zhao *et al.* (2024a) introduced pomegranate peel extract into SPI/*Artemisia sphaerocephala* Krasch. gum composite films. The film thickness, TS, and EAB were increased by 24.5%, 58.8%, and 30.5%, respectively, while water vapor and oxygen transmission rates were decreased. Xue *et al.* (2024) constructed preservation films for cherry tomatoes using SPI-polyphenol conjugates loaded with rose essential oil. Focusing on metal-phenolic networks (MPNs), Cheng *et al.* (2025) introduced Schiff base-metal phenolic networks into an oxidized corn starch/SPI system, increasing TS by approximately 72% and decreasing water vapor transmission rate by about 35%. Wang *et al.* (2025a) reported that MPN-modified SPI films exhibited >80% antimicrobial efficiency on blueberries and delayed fruit quality degradation in a 10-day test. Test results indicate that zein systems are frequently used to construct carriers for hydrophobic active substances and nanofibers, whereas SPI generally serves as a reactive cross-linked network platform in the design of composite films.

Structural Tailoring *via* Secondary/Tertiary Structure Modulation

The mechanical strength, moisture resistance, surface hydrophobicity, and active substance release behaviors of protein-based films are directly influenced by the conformational rearrangement of macromolecular chains. Thermal denaturation promotes the exposure of buried hydrophobic groups and partial sulfhydryl groups, affecting intermolecular hydrophobic association and disulfide bond recombination. Enzymatic cross-linking alters the topological structure of intermolecular covalent connections. Polyphenols, metal ions, and deep eutectic solvents influence the local structural order and free volume distribution of the protein matrix through hydrogen bonding, coordination, and conformational plasticization.

Regarding the reorganization of protein disulfide networks, the introduction of reducing agents directly alters the processing rheological characteristics of the system and intermolecular forces during film formation. Jiang *et al.* (2023b) systematically analyzed the effects of cysteine pretreatment on the physicochemical properties of SPI film-forming solutions and films (Fig. 6). Sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) analysis (Fig. 6a) indicated that cysteine cleaved the disulfide bonds linking the α and α' subunits of SPI, thereby reducing the apparent viscosity of the film-forming solution from 41.6 to 12.8 mPa·s (at a 1 mmol/L concentration), which improved the processing fluidity of high-concentration film-forming solutions. During the film drying process, the cleavage of disulfide bonds promoted the exposure of internal hydrophobic groups, leading to an increased proportion of hydrophobic interactions within the film (Fig. 6b). This molecular rearrangement based on tertiary structure unfolding decreased the water solubility of the film from 70.4% to 57.6%, improving the water resistance of the material without altering its tensile strength. However, when the cysteine concentration reached 4 mmol/L and above, X-ray diffraction (XRD, Fig. 6c) and scanning electron microscopy (SEM, Fig. 6d) results revealed that excessive cysteine formed crystalline aggregates on the film surface, resulting in a decrease in elongation at break. This study confirmed that regulating the thiol/disulfide exchange reactions of proteins via small-molecule reducing agents can quantitatively tune the rheological properties of film-forming solutions and the structural compactness of the final films.

Studies on the conformational evolution of SPI systems confirm the aforementioned mechanisms. Kang *et al.* (2024) analyzed the effect of transglutaminase (TGase) on the film-forming behavior of soy protein; spectroscopic data indicated that TGase promoted the transition of proteins from β-turns/random coils to β-sheets, thereby

altering the structural order and water stability of the film network. Research by Wang *et al.* (2023) on MPN-modified SPI demonstrated that polyphenol networks intervened in intermolecular protein interactions and interfacial adhesion. Zheng *et al.* (2025) plasticized SPI films using a β-cyclodextrin supramolecular deep eutectic solvent; conformational analysis revealed an increase in α-helix and β-turn content and a decrease in β-sheets, with the films reaching DPPH and ABTS scavenging percentages of 28.94% and 24.29%, respectively. This indicates that the introduction of plasticizers is accompanied by the resetting of local conformations and free volume within the protein matrix.

In the regulation of active substance loading and release, Li *et al.* (2025d) achieved the pH-triggered release of tannic acid by utilizing changes in the spatial conformation of SPI induced by environmental pH variations. This mechanism controls release kinetics by modulating intermolecular protein spacing and the exposure of binding sites, and was applied in shrimp preservation tests. Previously, Li *et al.* (2022b) introduced curcumin into SPI films *via* an organic solvent-free pH-driven system; results showed that curcumin was dispersed in an amorphous state and embedded into the protein network through hydrogen bonding and hydrophobic interactions. The resulting films had an EAB of 122 ± 6% and a WVP of approximately 1.70×10^{-10} g·m/(m²·s·Pa). These data indicate that pH-driven reconstitution affects the solid-state dispersibility of active substances and the toughness of the composite network.

For mixed protein systems, structural tailoring involves the control of microphase separation in multiphase systems. Phase separation occurs when compounding hydrophobic zein with hydrophilic proteins such as gelatin. Zulfikar *et al.* (2025) systematically analyzed the phase separation characteristics and structure-property correlations in gelatin/zein films. The results demonstrated that the final physical properties of the blended films are jointly governed by phase-domain scale, interfacial adhesion forces, and macromolecular segment migration behavior. Physicochemical characterization results indicate that quantitative interventions in the rheology, interfacial adhesion, gas barrier, and active delivery characteristics of protein matrices can be achieved by controlling the conformational rearrangements of secondary and tertiary structures.

To facilitate a quantitative comparison among the natural biopolymer matrices discussed above, Table 1 summarizes representative mechanical, barrier, and active properties reported for selected composite systems.

Because these data were obtained using different formulations, film dimensions, conditioning procedures, and analytical protocols, the absolute values primarily reflect the performance achieved under the specific conditions of each study. In particular, mechanical and barrier properties are sensitive to film thickness and environmental conditioning, whereas antimicrobial and antioxidant results depend strongly on the selected evaluation method. Therefore, comparisons are more meaningful when based on the relative changes between the modified and control films within the same study, while differences among independent studies should be interpreted as general performance trends rather than as a strict ranking of the polymer matrices.

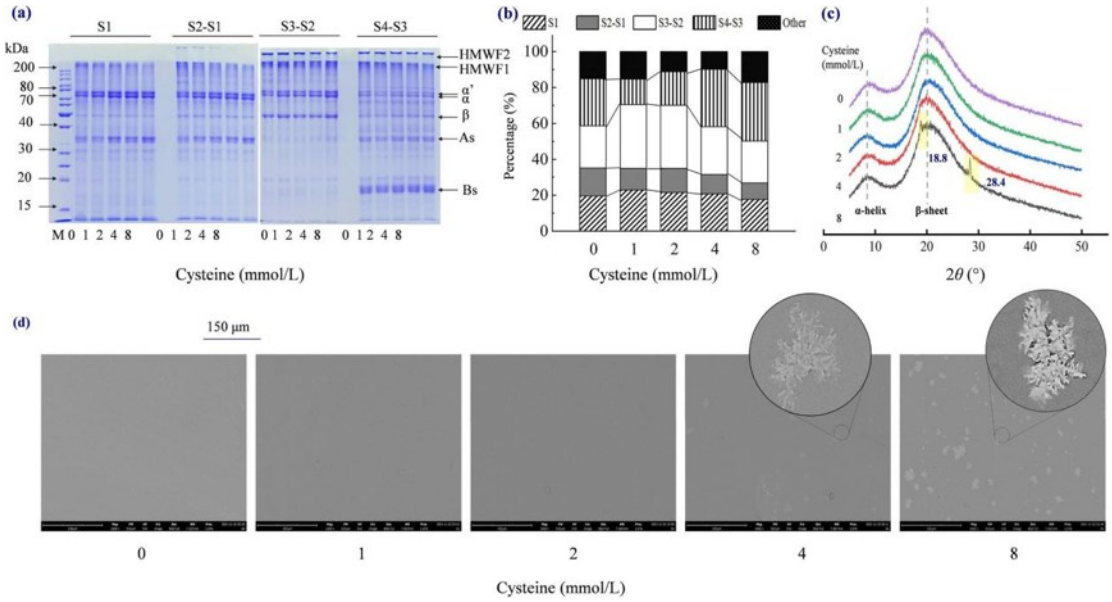

Fig. 6. Effects of cysteine pretreatment on the microstructure and intermolecular forces of SPI films: (a) SDS-PAGE protein patterns of films under different cysteine concentrations; (b) Proportion distribution of chemical bonds (ionic bonds, hydrogen bonds, hydrophobic interactions, and disulfide bonds) in the films; (c) XRD patterns of SPI films; (d) SEM images of the film surfaces (showing cysteine crystalline aggregates). (Jiang *et al.* (2023b), CC BY-NC-ND 4.0).

The mechanical response to active-agent incorporation is determined by the competition among reinforcement, plasticization, and defect formation rather than by the presence of the active component alone. At low or optimized loadings, hydrogen bonding, electrostatic interactions, hydrophobic associations, ionic or covalent crosslinking, and strong filler–matrix adhesion can restrict chain slippage and improve stress transfer, thereby increasing tensile strength or modulus. In contrast, liquid essential oils and some low-molecular-weight extracts may act as plasticizers by increasing chain mobility and free volume, commonly decreasing tensile strength while increasing elongation at break. When the loading exceeds the compatibility or dispersion capacity of the matrix, aggregation, phase separation, microvoids, and interfacial debonding interrupt stress transfer and promote premature fracture. The resulting mechanical properties are also affected by filler aspect ratio, crosslink density, crystallinity, porosity, plasticizer content, moisture conditioning, film thickness, and testing conditions. Consequently, improvements or deterioration should be interpreted as formulation- and condition-dependent outcomes rather than as universal effects of a specific active agent (Wang *et al.* 2022; Dong *et al.* 2024; Yun and Liu 2024; Cabrera-Barjas *et al.* 2025).

Table 1. Quantitative Comparison of Representative Natural Biopolymer-based Active Packaging Systems

Biopolymer Matrix	Representative System	Mechanical Properties	Barrier/Water-resistance Properties	Active Performance and Application	Reference
Starch	Cassava starch + 2% geranium essential oil	TS: 8.12 ± 0.30 → 3.09 ± 0.11 MPa; EAB: 41.59 ± 1.67 → 72.84 ± 3.55%	Not quantitatively reported	Inhibition-zone areas: 99.14 ± 3.21, 125.31 ± 2.58, and 126.57 ± 2.45 mm² against *E. coli*, *S. aureus*, and *L. monocytogenes*, respectively; increased flexibility but reduced strength	Wang *et al.* (2022)
Starch	Starch + 10 wt% $Ti_3C_2T_x$ MXene	TS: 9.9 → 19.1 MPa; Young's modulus: 456.5 → 1923.6 MPa	WVP ↓ 92.9%; oxygen permeability ↓ 74.0%; water contact angle: 55.3° → 84.8°	Strong mechanical/barrier reinforcement; complete soil degradation within 6 weeks	Dong *et al.* (2024)
Starch	Starch + jabuticaba peel phenolic extract	TS: 16.3 ± 0.7 MPa; EAB: 79.7 ± 3.1%	High transparency and UV-shielding; no unified permeability value reported	DPPH scavenging: 91.01 ± 0.5%; antimicrobial and pH-responsive color-changing functions	Luz *et al.* (2023)
Cellulose and derivatives	CMC/agar + CNC + shikonin	TS: 61.7 MPa	Improved water resistance and UV shielding; no directly comparable permeability value reported	Significant inhibition of L. *monocytogenes* and *E. coli*; multifunctional smart-film response	Roy *et al.* (2021)
Cellulose and derivatives	HEC + sulfated rice-bran polysaccharide (20%)	TS: 12.66 ± 0.33 → 33.04 ± 0.47 MPa	WVP: $4.21 \times 10^{-10} \rightarrow 1.15 \times 10^{-10}$ g·m^{-1}·s^{-1}·Pa^{-1}	DPPH scavenging: 77.83 ± 1.12%; distinct antibacterial inhibition zones	Chen *et al.* (2024a)
Cellulose and derivatives	CMC/PVA + cinnamaldehyde–tannin–metal nanoparticles	TS: 69.78 MPa; EAB: 104.4%	Water contact angle increased to 119.31°	Maximum DPPH scavenging: 89.4%; simultaneous strengthening and hydrophobic modification	Wang *et al.* (2025b)
Chitosan	Vanillin-crosslinked chitosan + green-tea polyphenols	TS: 20.9 ± 3 MPa	Reduced water solubility and moisture content; 100% UV shielding	About 70% release in the first 8 h, followed by sustained release up to 400 h; Fickian diffusion through evolving microchannels	Westlake *et al.* (2023a)
Chitosan	CS–CNF/VA25–Ca1.5 multiple-crosslinked film	Not numerically reported in the reviewed text	Oxygen permeability: 0.9 cm^3·μm·m^{-2}·d^{-1}·kPa^{-1}; intact in water >32 d	DPPH scavenging: 93.6%; extended strawberry shelf life at room temperature to 7 d	Zhao *et al.* (2025a)

Biopolymer Matrix	Representative System	Mechanical Properties	Barrier/Water-resistance Properties	Active Performance and Application	Reference
Chitosan	Chitosan + Indian gooseberry extract + AgNPs	TS: 29.29 ± 1.04 → 46.62 ± 0.82 MPa; EAB: 36.21 ± 1.87 → 89.39 ± 1.11%	WVTR decreased to 313.94 ± 1.81 $g \cdot m^{-2} \cdot d^{-1}$; reduced water absorption and solubility	Enhanced active performance; composite reached 93.42% mass loss by the end of month 2	Deb *et al.* (2025)
Alginate/ pectin	Sodium alginate + 2% $CaCl_2$ + 1% patchouli essential oil	TS: 31.8 MPa	WVP: 2.11 × 10^{-11} $g \cdot m^{-1} \cdot h^{-1} \cdot Pa^{-1}$	Improved thermal stability and inhibited mold growth on cherry tomatoes over 4 d	Asmadi *et al.* (2025)
Alginate/ pectin	Sodium alginate + 5 wt% quaternary-ammonium lignin–cinnamaldehyde	TS: 11.53 → 24.42 MPa	WVP decreased by 35.4%	Inhibition rates: 96% against *S. aureus* and 65% against *E. coli*; reduced weight loss and decay in persimmons/citrus	Miao *et al.* (2025)
Alginate/ pectin	Pectin + lemon essential-oil microcapsules	TS: 12.28 ± 1.27 → 14.68 ± 1.42 MPa; EAB: 11.52 ± 0.12 → 20.05 ± 0.78%	Hydrophobic microdomains and interconnected channels formed; no unified WVP value reported	DPPH scavenging: 21.37 ± 0.001 → 63.60 ± 0.001%	Akachat *et al.* (2025)
Protein	Electrospun gelatin/zein + cinnamaldehyde + thymol	TS: 1.30 MPa; EAB: 185%	Water contact angle: 85.1°; WVTR: 3.1 × 10^{-8} $g \cdot mm^{-1} \cdot h^{-1} \cdot Pa^{-1}$	Co-delivery of two volatile antimicrobials for strawberry packaging; high flexibility	Wu *et al.* (2023)
Protein	Gelatin + zein–quercetin nanoparticles	TS: ~3.2 MPa; EAB: ~142%	Water-vapor and oxygen transmission rates ↓ 78.4% and 76.9%; water contact angle: 112.0 ± 0.6°	DPPH scavenging: 64.9 ± 0.7%; improved hydrophobicity and antioxidant activity	Xu *et al.* (2025a)
Protein	Chitosan/WPI + betacyanin + carbon dots	TS: 79.42–91.74 MPa	WVP: 6.90 × 10^{-11} → 2.54 × 10^{-11} $g \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$	Inhibition zones: 20 ± 1.2 mm (S. aureus) and 15 ± 0.36 mm (E. coli); colorimetric smart-indicator function	Kiani-Salmi *et al.* (2025)
Protein	SPI film containing thymol-loaded high-internal-phase emulsion	TS: 4.47 MPa; EAB: 160.83%	WVP: 1.15 × 10^{-10} $g \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$	Higher thymol encapsulation efficiency and sustained antimicrobial release than conventional O/W-emulsion or free-oil films	Zhao *et al.* (2024b)

Notes: TS, tensile strength; EAB, elongation at break; WVP, water-vapor permeability; WVTR, water-vapor transmission rate; WPI, whey-protein isolate; SPI, soy-protein isolate; CMC, carboxymethyl cellulose; HEC, hydroxyethyl cellulose; CNC, cellulose nanocrystal; CNF, cellulose nanofiber; DPPH, 2,2-diphenyl-1-picrylhydrazyl. "↓" indicates a decrease relative to the corresponding control. Values and author–year citations are taken from studies already discussed in the manuscript. Values were obtained under different experimental conditions and should therefore be interpreted as representative trends rather than directly comparable rankings.

Active Functionalities and Mechanistic Insights

The multifunctional improvements summarized above may arise from either additive effects or genuine synergy among the active components. Synergy should be assigned only when the combined response exceeds the expected contribution of the individual components, as supported by appropriate single-component controls or quantitative interaction analysis. In the absence of such evidence, the observed enhancement is more appropriately attributed to combined or complementary actions. For example, membrane disruption, reactive oxygen species generation, and radical scavenging may occur concurrently, but the coexistence of these mechanisms alone does not necessarily demonstrate a synergistic effect.

Antimicrobial action modes

The antimicrobial function of biodegradable active packaging can be elucidated through mechanisms such as cell membrane disruption, oxidative stress, and metabolic interference. Studies indicate that the antimicrobial efficacy of such packaging systems is determined by multiple coupled processes, including the perturbation of cell wall/membrane structures, dissipation of transmembrane electrochemical gradients, leakage of intracellular proteins and nucleic acids, accumulation of reactive oxygen species (ROS), impedance of energy metabolism, as well as the inhibition of biofilm formation and reduction in population adaptation capacity (Acharya *et al.* 2025). Jiao *et al.* (2025) noted that antimicrobial molecules not only induce classical membrane rupture but also act on specific microbial components and molecular targets, involving multiple concurrent target mechanisms. Therefore, as an interfacial system, the antimicrobial outcome of active packaging is influenced by the release rate, surface accessibility, and microbial contact efficiency of the active substances, as well as the food matrix.

Cell envelope disruption is one of the fundamental antimicrobial pathways. An analysis of cellulose-based antimicrobial surfaces by Marquez *et al.* (2025) indicated that the activity of chitosan-based coatings against Gram-positive bacteria correlates with the electrostatic interactions between their protonated $–NH_3^+$ groups and the negatively charged components in the bacterial cell wall. Conversely, inorganic nanomaterials such as ZnO and Ag exert inhibitory effects against various foodborne microorganisms primarily through membrane damage pathways. In antimicrobial peptide systems, Jiao *et al.* (2025) described that the mechanisms of nisin and ε-polylysine involve lipid II binding, pore formation, ion efflux, and destabilization of cell membrane functions. Wang *et al.* (2024a) confirmed that various milk-derived proteins altered the antimicrobial performance of nisin through self-assembly; lactoferrin-nisin nanoparticles (diameter approx. 29.83 ± 2.42 nm) exhibited inhibitory capacity against *Listeria monocytogenes*, *Staphylococcus aureus*, and *Bacillus cereus*, with the primary mechanism being enhanced disruption of the cell membrane. This indicates that interfacial accessibility and membrane targeting efficiency directly affect the antimicrobial efficacy of active substances.

The membrane damage mechanism has been experimentally verified in specific packaging applications. How *et al.* (2024) incorporated *Persicaria minor* essential oil nanoemulsions into CMC/chitosan composite films; films containing 12% (v/v) nanoemulsion produced inhibition zones of 7.19 mm and 7.85 mm against *Escherichia coli* and *Bacillus subtilis*, respectively, accompanied by altered film surface structures and increased antioxidant activity.

Addressing the specific mechanisms of cell envelope disruption, Chang *et al.* (2025) thoroughly investigated a sustained-release antimicrobial film based on modified

tapioca starch/chitosan loaded with clove essential oil (CEO) (Fig. 7). As depicted in Figs. 7A and B, the 1.25% CEO composite film exhibited inhibition zones of 5.02 ± 0.31 mm and 4.23 ± 0.28 mm against *E. coli* and *S. aureus*, respectively. Micro-morphological analysis (Fig. 7C) visually demonstrated the physical disruption of the target bacteria caused by film contact: post-treatment, *E. coli* cells underwent deformation and medial perforation, accompanied by the efflux of intracellular contents; *S. aureus* lost its smooth spherical morphology, developing surface folds and undergoing severe collapse. Quantitative analyses based on absorbance at 260 nm and protein leakage confirmed that the core active component of the essential oil (eugenol) compromised the structural integrity and permeability of the bacterial cell membrane, leading to an acute leakage of macromolecules such as nucleic acids and proteins. This intracellular microenvironmental destabilization, initiated by plasma membrane perforation, constitutes the core physicochemical pathway for the antimicrobial efficacy of this system, ultimately extending the shelf life of tested bread to 9 days. Li *et al.* (2025a) prepared PVOH/QAC core-shell nanofiber membranes loaded with oregano essential oil *via* emulsion electrospinning, achieving a maximum inhibition zone of 23.13 ± 0.72 mm. The release kinetics conformed to Fickian diffusion and first-order kinetic models (R^2 = 0.9570–0.9997); the film decelerated the increase rates of pH, TVB-N, TBARS, and TVC in chicken breast at 4 °C, extending the shelf life by 4 days.

Oxidative stress is another antimicrobial mechanism. An analysis of 158 publications by Zhao *et al.* (2025b) indicated that the antimicrobial action of natural phenolics involves multiple concurrent mechanisms: 72% of the studies detected ROS generation, 58% involved membrane disruption, and 41% involved DNA interactions, thereby supporting a cascade model of "membrane damage-oxidative imbalance-genetic interference". Research by Wang *et al.* (2024b) on flaxseed polyphenol extracts demonstrated that the antimicrobial process is accompanied by increased membrane permeability, protein leakage, membrane depolarization, and decreased intracellular ATP levels, indicating a coupled correlation between oxidative stress and energy metabolism imbalance. Lei *et al.* (2024) found that fermented *Adina rubella* extract exerted inhibition against *L. monocytogenes* through pathways including cell wall damage, increased membrane permeability, nucleic acid leakage, and ROS variations, based on which corresponding antimicrobial packaging films were constructed. Reactive nitrogen and oxygen species can also contribute to microbial inactivation (Wang *et al.* 2024c).

In inorganic nanocomposite surfaces, structural design regulates the generation and accumulation of ROS. Chen *et al.* (2025b) investigated the inhibitory effect of LDPE/SF/5%ZnO films containing an antifogging agent against *Pseudomonas fluorescens* in lettuce. The results showed that the addition of the antifogging agent increased the retention and release rates of nano-ZnO; the system exerted antimicrobial action by increasing Zn^{2+} release, enlarging the contact area between nanoparticles and bacterial surfaces to promote intracellular substance leakage, and inducing ROS generation. The γ-CD-MOF/Au functional film constructed by Guo *et al.* (2026) for refrigerated fish fillet packaging reduced the populations of *E. coli* O157:H7 and *S. aureus* by approximately 99.4% and 80%, respectively, within 24 h. On day 4 of storage, the pH was maintained at 6.70 ± 0.02 and TVB-N at 8.71 mg/100 g. The data indicates that nanocarriers and functional surfaces regulate the bactericidal efficiency per unit of active substance by altering the state of interfacial accumulation and oxidative pressure.

The antimicrobial process also involves metabolic interference, wherein microorganisms experience sub-lethal dysregulation stages during inhibition, including

disruption of membrane homeostasis, impairment of energy supply, imbalance in substance transport, and a decline in repair capacity. Studies by Zhu *et al.* (2025a) demonstrated that perilla leaf essential oil (PLEO) caused compromised cell membrane integrity, cytoplasmic leakage, membrane depolarization, and intracellular ATP depletion in *Shigella flexneri*, inducing ROS accumulation and reducing catalase activity. Untargeted metabolomics analysis revealed that the affected metabolic pathways included amino acid metabolism, lipid metabolism, and energy metabolism. Zhang *et al.* (2025d) utilized metabolomics to analyze the effect of carnosic acid on *Shewanella putrefaciens*, noting that its mechanism involves the remodeling of bacterial metabolic networks and the perturbation of oxidative respiration processes. Research by Diao *et al.* (2025) on α-lactalbumin-thymol complexes indicated that the protein carrier altered the dispersion state of thymol in the aqueous phase and its pathway of action on the membrane, with MIC values of 336 and 224 μg/mL against *E. coli* and *S. aureus*, respectively.

Addressing the biofilms formed by microorganisms at packaging interfaces or food surfaces, related studies have evaluated the intervention capacity of active packaging systems on biofilm formation and attachment behaviors. Zhu *et al.* (2025b) found that laurel essential oil reduced the biofilm formation and extracellular polymeric substance (EPS) content of *S. putrefaciens* in liquid media. It also inhibited biofilm establishment on shrimp surfaces as well as on contact surfaces such as stainless steel, glass, and silica gel. Zhang *et al.* (2024a) analyzed the inhibitory effect of chitosan-grafted gentisate acid derivatives against *P. fluorescens*, identifying that their targets encompass cellular structure, metabolic systems, antioxidant systems, and biofilms. Furthermore, Zhang *et al.* (2025a) studied the effect of lauroyl arginate ethyl (LAE) on *L. monocytogenes*, showing that the substance controlled microbial contamination in an enoki mushroom system by increasing membrane permeability, inducing membrane depolarization, and causing protein and nucleic acid leakage.

Within active packaging systems, photo-responsive antimicrobial mechanisms have also been incorporated into the scope of research. Analyses by Yang *et al.* (2025a) and Chen *et al.* (2025d) indicated that photodynamic, photothermal, and photocatalytic active films can achieve ROS release and localized thermal effects upon light signal stimulation, providing an externally triggered pathway for interfacial inactivation. Research by Wang and Gong (2025) on starch/CMC-based photodynamic antimicrobial packaging films demonstrated that the packaging inhibited microbial proliferation during the storage of snap beans. Broad-targeted metabolomics analysis showed that photodynamic packaging regulated metabolic networks of phenolic acids, flavonoids, lipids, amino acids, and their derivatives, thereby decelerating the deterioration of the target's appearance and nutritional quality.

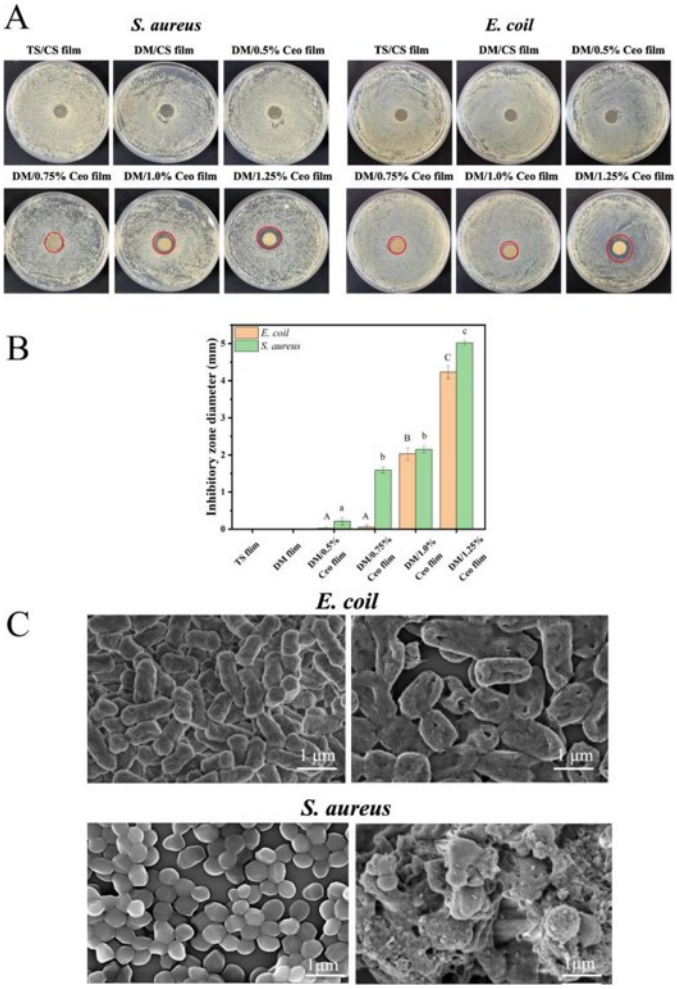

Fig. 7. Antimicrobial efficacy and mechanism characterization of sustained-release starch/chitosan films loaded with clove essential oil: (A, B) Morphology and diameter statistics of inhibition zones against *S. aureus* and *E. coli* by composite films with different CEO concentrations; (C) Scanning electron microscopic image comparison of bacteria before (left column) and after (right column) treatment with the 1.25% CEO film. (Reproduced from Chang *et al.* (2025), CC BY 4.0).

Summarizing the experimental data, the antimicrobial action of biodegradable active packaging encompasses multi-target and multi-stage mechanisms. Active substances undergo localized accumulation at the contact interface. They induce ion imbalance, intracellular substance leakage, and membrane potential decline through cell wall/membrane disruption. They are accompanied by ROS accumulation, alterations in enzyme activity, and energy metabolism disorders. At a macroscopic level, they interfere with biofilm formation and attachment behaviors. Differences in the efficacy of the same antimicrobial agent across various matrices are influenced by the matrix's capacity to regulate its diffusion behavior, local hydration state, and interfacial contact mode. Therefore, the investigation of antimicrobial packaging mechanisms relies on experimental evidence spanning multiple dimensions, including membrane integrity, ROS, ATP/enzyme activity, metabolomics, and biofilms.

Antioxidant and scavenging mechanisms

The antioxidants and scavenging mechanisms in active packaging are not limited to the physical addition of a single antioxidant; rather, they encompass a multi-level

regulatory system involving radical scavenging, ROS inhibition, oxygen/ethylene depletion, and the blockade of photo-induced oxidation. Current studies indicate that chemical radical scavenging assays, such as DPPH and ABTS, primarily characterize the hydrogen/electron-donating capacity of the active components within the films. The actual preservation efficacy is concurrently governed by the dispersion state of the active substances within the polymer network, their migration and release kinetics, their coupling characteristics with lipid oxidation chain reactions, and the regulation efficiency of deteriorative factors such as oxygen and ethylene in the packaging headspace. This section focuses on the functional transformation process of antioxidant mechanisms at the packaging interface.

Radical scavenging represents the fundamental antioxidant pathway in biodegradable active packaging. Its core mechanism involves polyphenols, vitamins, natural extracts, or carbon-based nanostructures within the matrix donating hydrogen atoms or electrons to free radicals, thereby terminating the chain propagation of lipid oxidation or enzymatic browning (Cazón *et al.* 2025; Sani *et al.* 2025). This mechanism has been extensively validated in packaging systems derived from plant by-products. Ludka *et al.* (2024) utilized brewer's spent grain extract to construct starch/PVOH composite films, determining the IC_{50} values of the extract in ABTS and DPPH assays to be 2.0 ± 0.6 μg/mL and 196.05 ± 18.66 μg/mL, respectively, endowing the films with sustained polyphenol release and antioxidant properties. Vieira *et al.* (2024) introduced antioxidant extracts from brewer's spent grain into cassava starch/PVOH biodegradable packaging, achieving antioxidant functionality while maintaining basic film-forming properties. These studies indicate that the structural stability and controlled release of polyphenolic substances within the matrix are prerequisites for establishing a localized reducing environment at the food interface.

Addressing the correlation between antioxidant release kinetics and radical scavenging efficacy, Westlake *et al.* (2023a) constructed a vanillin cross-linked chitosan film for the controlled release of green tea polyphenols (Fig. 8). As illustrated in Figs. 8a and 8b, the release of polyphenols in a 50% ethanol food simulant exhibited an initial burst release phase (first 8 h), followed by a stable controlled release phase lasting up to 400 h. Fitting the release data with Korsmeyer–Peppas and Higuchi models (Figs. 8d, 8e) confirmed that the process was primarily diffusion-driven. This multi-stage release kinetics ensured that the green tea polyphenols continuously exerted antioxidant effects (Fig. 8c), maintaining a DPPH radical scavenging percentage of >80% across all tested concentrations. This study quantitatively reveals the dependence among the degree of polymer network cross-linking, polyphenol sustained-release profiles, and long-term radical scavenging capacity.

The correlation between high *in vitro* radical scavenging rates and the actual inhibition of food oxidation has received significant attention in recent studies. A transparent bioplastic film based on PVA/chitosan/acetylated lignin-halloysite nanotubes (PC-HALG) developed by Bao *et al.* (2025) demonstrated that the UV-A and UV-B shielding percentages of the film increased by 1347% and 617%, respectively. Under UV-irradiation, the film reduced the oxidation degree of pecan oil by 81.3% to 92.2%, indicating its effectiveness in inhibiting the photo-oxidation process of lipid-rich foods. Tran *et al.* (2025) introduced broccoli leaf-derived carbon dots into chitosan/gelatin films; at an addition level of 5%, the TS of the film reached 80.3 MPa, the DPPH scavenging percentage was approximately 90%, and water solubility decreased to about 13%. Application tests revealed that the film reduced UV damage in green apples and mitigated

strawberry deterioration, outperforming commercial PE films in overall performance. Experimental data suggest that the performance of advanced antioxidant packaging relies on the physicochemical coupling of radical scavenging, light shielding, and structural stabilization.

UV-shielding, serving as a critical mechanism in the antioxidant systems of active packaging, mitigates the photo-induced oxidative degradation of lipids, pigments, vitamins, and aroma molecules by absorbing or blocking high-energy photons in the 200 to 400 nm range (Sani *et al.* 2025). Research by He *et al.* (2026) on a PBAT/PLA/rosemary extract (RM) system showed that when the RM addition level was ≥ 0.5%, the film's blocking percentages against both UVA and UVB exceeded 90%. Furthermore, the mass loss of this system exceeded 90% after 240 days of composting, achieving an integration of antioxidant properties, UV shielding, and biodegradability. A multifunctional TA-PS/CMC film developed by Xie *et al.* (2025) demonstrated that tannic acid not only endowed the film with a selective UV shielding of >90% but also generated singlet oxygen under visible light excitation, thereby forming a dual-modal photodynamic regulation of "UV shielding–visible light utilization," which consequently enhanced the antioxidant and preservation effects on strawberries. This mechanism reduces the initiation probability of oxidative chain reactions at the source by attenuating the rate of photo-induced radical generation.

In addition to radical scavenging and light shielding, the oxygen scavenging mechanism aims to actively consume residual or permeating oxygen in the packaging headspace through chemical reactions, playing a specific role in protecting high-lipid, baked, and browning-susceptible foods (Jain *et al.* 2025). The cited authors summarized advancements in non-iron oxygen scavenging systems, encompassing antioxidant types (*e.g.*, ascorbic acid, α-tocopherol), hydrocarbon auto-oxidation types, enzymatic types, and polyphenol-based materials. The reported oxygen absorption capacities range from 6.44 mL O_2/g (based on α-tocopherol) to 200 mL O_2/g (based on polybutadiene), with such reactions frequently activated by humidity, pH, or UV light. For biodegradable packaging, oxygen scavenging extends the physical isolation mechanism of traditional high-barrier films, forming a combined protection mode of "barrier + reactive consumption".

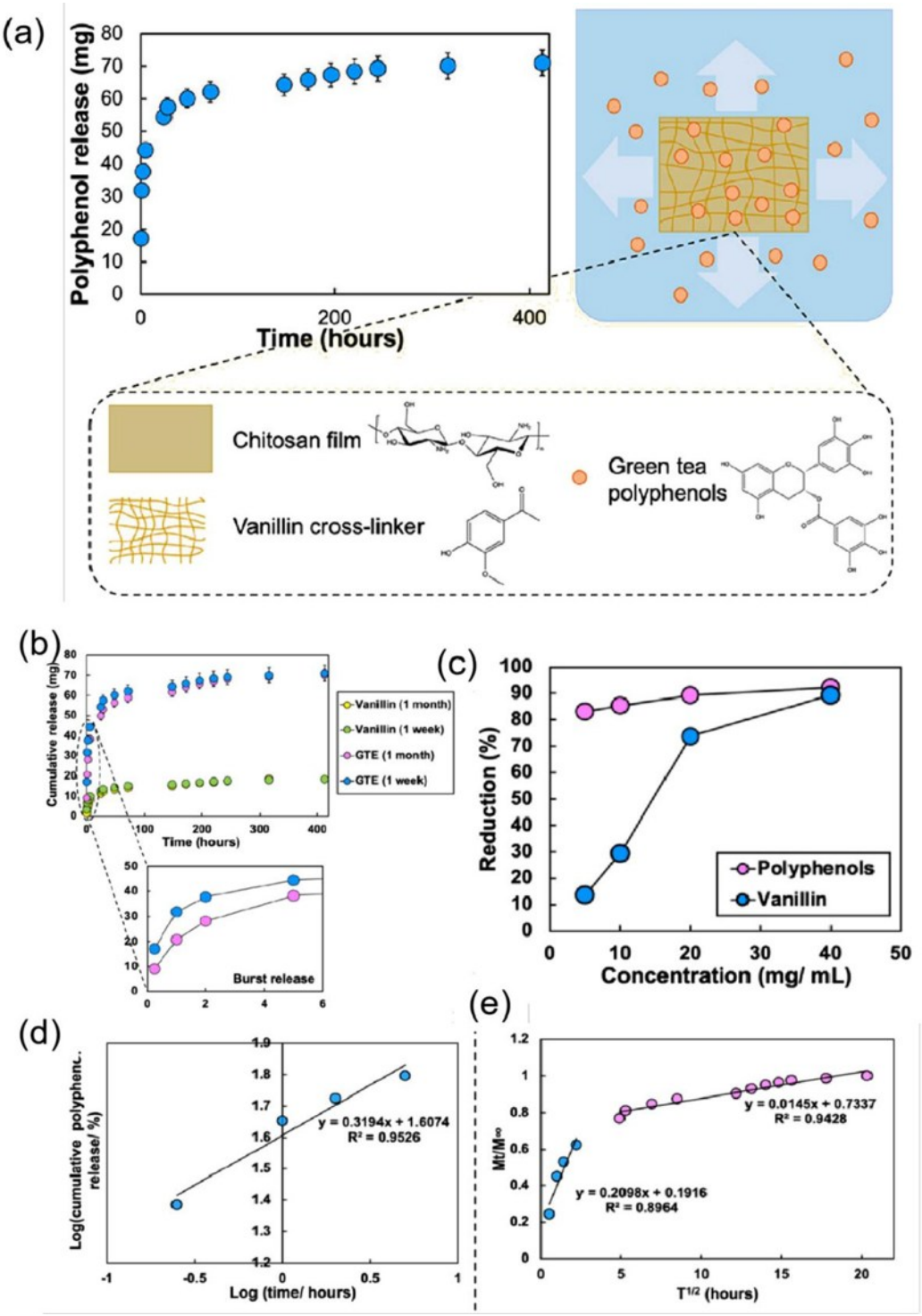

Fig. 8. Controlled release kinetics and antioxidant efficacy of green tea polyphenols in a vanillin cross-linked chitosan film: (a, b) Cumulative release profile of polyphenols in a 50% ethanol simulant, with the inset showing the burst release effect during the initial 8 h; (c) DPPH radical scavenging rates of green tea polyphenols and vanillin at varying concentrations; (d) Korsmeyer–Peppas kinetic model fitting of the release data; (e) Higuchi model fitting of the release data. (Westlake *et al.* (2023a), CC BY 4.0).

In fruit and vegetable packaging, ethylene scavenging serves as a crucial intervention to control deterioration. Ethylene significantly accelerates respiratory climacteric effects, including softening, yellowing, and tissue browning. Hong *et al.* (2025) constructed an active film of TiO_2-doped Ce-MOF/CNF; under UV irradiation, 0.08 g of this composite material degraded 100 ppm of ethylene within 6 h, while simultaneously reducing the film's transmittance at 280 nm to 1.54%, thereby delaying the postharvest ripening of avocados. Khan *et al.* (2025) incorporated TiO_2-functionalized Bi-MOF into cellulose nanofiber/gelatin films; this system achieved UV-B and UV-A blocking effects of 99.6% and 97.8%, respectively, and extended the shelf life of bananas by 10 days. Studies have demonstrated that highly efficient ethylene scavenging relies on the combined contributions of targeted gas adsorption/enrichment, catalytic degradation, and the physical barrier properties of the matrix.

A complementary relationship is frequently observed between gas barrier properties and antioxidant functions. A composite spray coating (K-NPs-15) based on konjac glucomannan/KGM-quaternized chitosan-tannic acid nanoparticles developed by Deng *et al.* (2024) concurrently exhibited antioxidant, antimicrobial, and UV-shielding functions, with an oxygen permeability as low as 1.93×10^{-13} $(cm^3 \cdot cm)/(cm^2 \cdot s \cdot Pa)$, effectively extending the shelf life of bananas. When polyphenols or nanofillers enhance the compactness, hydrophobicity, and free-volume constraints of the film matrix, the gas migration rate simultaneously decreases, achieving an overlay of chemical scavenging and physical barrier. Consequently, current preservation evaluation systems comprehensively consider macroscopic indicators such as color retention, TBARS/peroxide values, headspace gas dynamics, and nutrient retention rates, to fully validate the oxidation inhibition efficacy of the films.

In summary, the antioxidant and scavenging mechanisms in active packaging constitute a multi-pathway integrated system comprising "radical termination–oxygen/ethylene consumption–photo-induced oxidation inhibition". Radical termination relies on the electron-donating capacity of the active components; media scavenging diminishes deterioration driving forces by consuming or catalytically degrading oxygen and ethylene; and UV shielding maintains food stability by attenuating the initiation phase of photo-oxidation (Li *et al.* 2022; How *et al.* 2024; Lei *et al.* 2024; Wang *et al.* 2024a,b; Chang *et al.* 2025; Jiao *et al.* 2025; Li *et al.* 2025a,e; Marquez *et al.* 2025; Zhao *et al.* 2025b; Zulfikar *et al.* 2025). These research systems indicate that the antioxidant design of film materials necessitates a comprehensive assessment of active component stabilization, intra-matrix mass transfer resistance, and validation within real food models, thereby establishing a distinct structure-mechanism-function correlation.

Mass Transfer and Controlled Release Kinetics

In active packaging systems, the efficacy of active substances is directly influenced by their release rate, time window, and spatial distribution on the food surface or within the packaging headspace. Controlled-release packaging (CRP) aims to maintain an effective concentration range of active substances during the storage period. An excessively rapid release leads to early depletion, while an overly slow release fails to reach the threshold required to inhibit oxidation or microbial proliferation. Current mass transfer studies attribute the release of active substances to the coupling of three mechanisms: diffusion, swelling, and matrix biodegradation. With the introduction of nanocarriers, core-shell fibers, multilayer films, and stimuli-responsive networks, the regulatory dimensions of the interfacial mass transfer process have significantly expanded (Xu *et al.* 2025b; Zhang

et al. 2025e). Nanofiber systems containing eugenol-loaded silk-fibroin nanoparticles or basil-oil-loaded cationic liposomes have further demonstrated sustained release together with antibacterial activity (Lin *et al.* 2022; Li *et al.* 2022a).

In release kinetic models, the mass transfer process is jointly governed by concentration gradient-driven molecular diffusion and the structural relaxation of the polymer network. When the system is diffusion-dominated with minimal matrix structural changes, the release profiles typically conform to Higuchi, Fickian diffusion, or first-order kinetic models. In swelling-controlled systems, water uptake induces polymer-chain relaxation, matrix expansion, and pore opening, so that active-agent release is governed by the coupling between molecular diffusion and network reconfiguration. In degradation-controlled systems, hydrolysis, enzymatic cleavage, carrier dissociation, or matrix erosion progressively liberates the active agent, and the release rate is therefore related to bond-cleavage kinetics, matrix mass loss, and environmental conditions. When the film matrix concurrently undergoes water absorption, swelling, pore expansion, interfacial dissociation, or localized degradation, semi-empirical models such as Korsmeyer–Peppas, Ritger–Peppas, and Weibull may be more suitable for characterizing the "diffusion–relaxation" coupling process (Cui *et al.* 2024; Yang *et al.* 2025b). The fitting parameters and physical significance of the release models are influenced by the type of active substance, carrier topological structure, simulant polarity, and microenvironmental conditions. The discrepancy between Fickian and non-Fickian diffusion behaviors essentially reflects the ratio between the molecular diffusion rate and the polymer network reconfiguration rate. Because diffusion, swelling, and degradation may occur simultaneously in hydrophilic biopolymer matrices, the release mechanism should not be assigned solely according to the highest fitting coefficient, but should also be supported by swelling, mass-loss, morphological, and structural evidence.

Humidity-responsive release is a mass transfer mechanism that utilizes a high-humidity microenvironment as a trigger signal. An increase in environmental relative humidity (RH) induces water absorption and swelling or pore opening in hydrophilic matrices, thereby accelerating the release of volatile essential oils, phenolic molecules, or gases. Tian *et al.* (2024) constructed TTO-HKUST-1@ALG moisture-responsive hydrogel beads; through alginate/Cu^{2+} cross-linking and *in situ* growth of HKUST-1 to form a hierarchical porous structure. The loading capacity of tea tree oil reached 21.6%. As the relative humidity was increased from 45% to 95%, the cumulative release of the essential oil increased from 33.9% to 71.0%, extending the shelf life of fresh-cut pineapples. Cui *et al.* (2024) utilized MCM-41 to construct an environment-responsive potato starch film (THY–MCM-41/PS); the release rate of thymol positively correlated with temperature and relative humidity, conforming to a first-order kinetic model ($R^2 > 0.980$). The film achieved a tensile strength of 7.18 MPa and delayed the sensory quality degradation of strawberries during storage at 25 °C and 50% RH.

In addition to small-molecule volatiles, humidity can also drive the *in-situ* generation and sustained release of reactive gases. Liu *et al.* (2024) introduced sodium chlorite and tartaric acid into a PLA/PBAT system; moisture absorption facilitated contact between reaction substrates, realizing the continuous release of ClO_2 gas, which achieved surface sterilization and ethylene degradation. Zhang *et al.* (2025c) utilized the hygroscopicity of chitosan to regulate the release rate of ClO_2. At a chitosan addition level of 4 wt%, the water vapor transmission rate of the film increased by 41.41%, the water contact angle decreased by 24.4%, and the ClO_2 release amount at 72 h increased by 2.81 times, maintaining a DPPH scavenging rate of 96.3% at 96 h. The data indicate that the

programmed release of reactive gases can be controlled by regulating the swelling and water permeability of the matrix.

pH-Responsive release utilizes localized pH fluctuations caused by the accumulation of organic acids, amines, or protein degradation products during food spoilage to trigger the deprotonation/protonation of polymer segments, dynamic bond cleavage, or carrier structure rearrangement. Liu *et al.* (2025b) developed an alliin@MIL-101(Fe)-functionalized starch bilayer film, comprising an amino-modified starch inner layer and a modified PVA/PLA outer layer; under acidic conditions, microenvironmental changes triggered the release of alliin, achieving a cumulative release of 74% over 36 h. In the eugenol@ZIF-8/PVA-HACC film constructed by Liu *et al.* (2026), the eugenol-loaded ZIF-8 exhibited a cumulative release of 32.2% over 4 h at pH 6, compared to only 0.61% at pH 7. Upon incorporation into the matrix, the film's water contact angle reached 92.5°, and the inhibition against *E. coli* was 88%. Test results indicate that the structural response of the carrier to specific pH ranges determines the peak release of active substances.

In pH-responsive carriers, the dissolution kinetics of microporous materials directly affect the release profile. Li *et al.* (2025c) reported a smart film (CEO@SOM-ZIF-8) based on clove essential oil and ordered macroporous ZIF-8. The release process followed Ritger–Peppas kinetics, with the fitted rate constants (k) under pH 6.0 and pH 7.0 conditions being 0.0822 h^{-n} and 0.0168 h^{-n}, respectively, confirming that acidic conditions accelerated matrix reconfiguration and drug release. In a 14-day blueberry storage test, the film (4% CEO@SOM-ZIF-8) maintained a total phenolic content of 110.92 mg/L; concurrent migration tests revealed that the migration of Zn^{2+} in a 70% ethanol food simulant was below the instrumental detection limit.

In pH-responsive carriers, the topological structure and dissolution kinetics of microporous materials directly determine the release profile of active molecules. Addressing this mechanism, Li *et al.* (2025c) utilized single-crystalline ordered macro-microporous ZIF-8 (SOM-ZIF-8) as a sustained-release carrier for clove essential oil (CEO) to construct a pH-responsive smart film (Fig. 9). Physicochemical characterization (Figs. 9a–f) revealed that SOM-ZIF-8 possesses a highly ordered porous structure (specific surface area of 2140 m^2/g, average pore size of ~1.08 nm), achieving a CEO loading capacity of 660.6 ± 2.4 mg/g. In *in vitro* release assays (Figs. 9g, h), the release of CEO exhibited significant pH dependence; the release kinetics conformed to the Ritger–Peppas model, with fitted rate constants (k) of 0.0822 h^{-n} and 0.0168 h^{-n} at pH 6.0 and pH 7.0, respectively, confirming that a mildly acidic environment accelerates the relaxation of the ZIF-8 framework and the diffusion of guest molecules. During a 14-day blueberry storage test, this controlled-release network (containing 4% CEO@SOM-ZIF-8) maintained the total phenolic content of the fruit at 110.92 mg/L. Concurrent migration tests demonstrated that the migration of Zn^{2+} in a 70% ethanol food simulant was below the instrumental detection limit, validating the chemical safety of the carrier at the food contact interface.

The temperature-responsive release mechanism is based on variations in diffusion coefficients induced by thermodynamic phase transitions or intensified thermal motion of molecular chains, commonly utilized to address temperature fluctuations in cold chain logistics. Shen *et al.* (2023a) developed THY@COF/PCL nanofibrous films *via* solution blow spinning. The COF carrier possessed a porous structure with a THY loading capacity of 30.4%, and the composite films showed temperature-responsive and long-term thymol release, together with enhanced barrier performance, biocompatibility, and antibacterial activity, indicating their potential for active packaging under warm-storage conditions. In a review by Yang *et al.* (2025b), it was noted that electrospun systems (*e.g.*, core-shell

fibers) and multilayer hydrocolloid networks can alter the mass transfer resistance of active molecules by adjusting the specific surface area and internal porosity. These structural features can mitigate initial burst release, prolong the steady-state release period, and provide a structural foundation for multi-stimuli coupling of temperature, humidity, and pH.

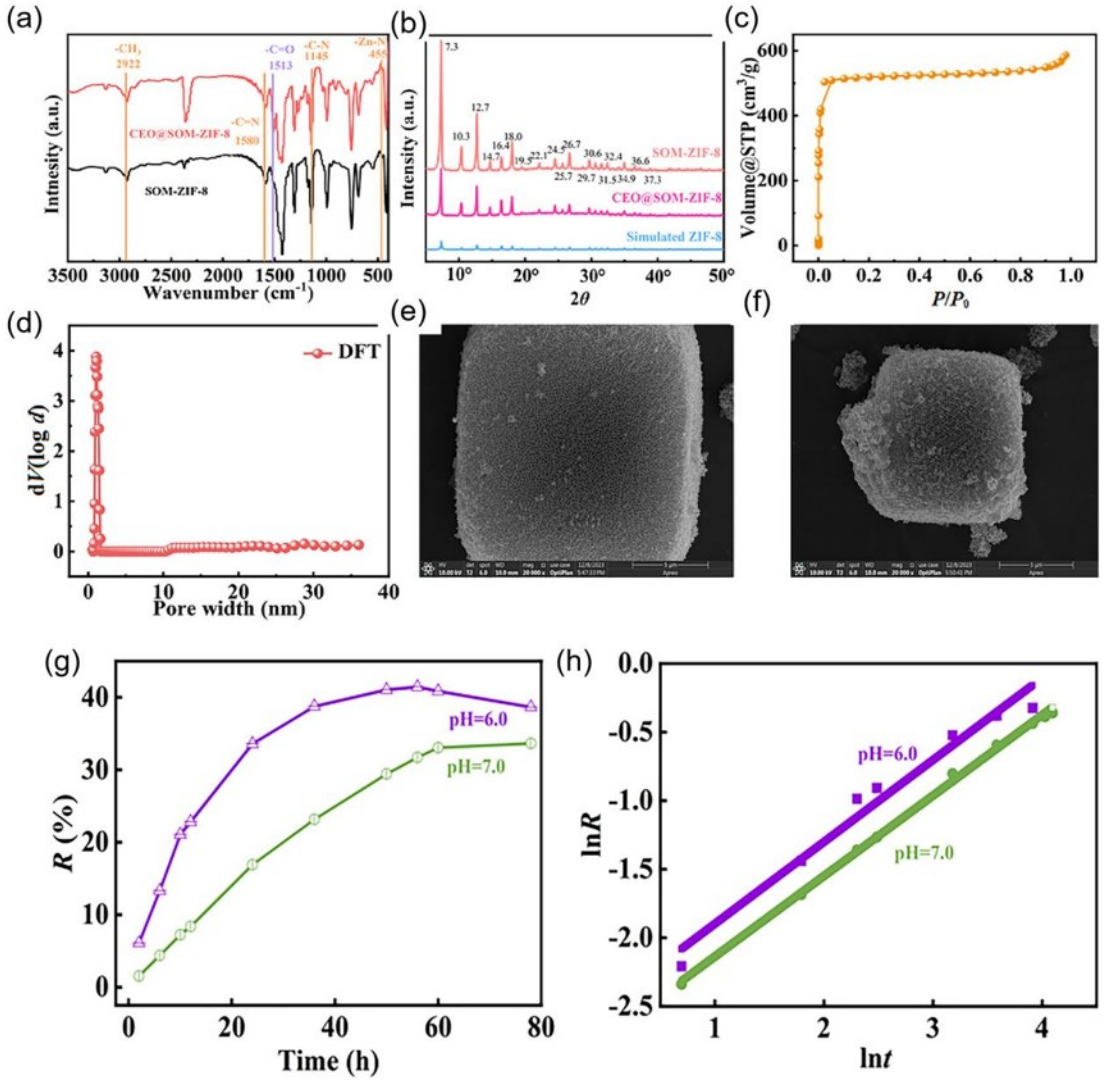

Fig. 9. Carrier structural characterization and pH-responsive release kinetics of CEO based on ordered macroporous ZIF-8 (SOM-ZIF-8): (a) FT-IR spectra; (b) XRD patterns; (c) N_2 adsorption–desorption isotherm; (d) Pore size distribution; (e, f) SEM images of SOM-ZIF-8 and CEO@SOM-ZIF-8; (g) Cumulative release curves of CEO at pH 6.0 and 7.0; and (h) Ritger–Peppas kinetic model fitting of the release data. (Reproduced from Li *et al.* (2025c), CC BY 4.0).

Environmental responsiveness should be distinguished from long-term functional stability. In hydrophilic biopolymer matrices, elevated relative humidity can plasticize the polymer network, increase swelling and water-vapor permeability, reduce mechanical integrity, and accelerate active-agent diffusion; repeated high-humidity exposure may therefore cause irreversible barrier loss or premature depletion of active compounds. Increasing temperature generally enhances molecular diffusion and volatilization and may

accelerate the oxidation or degradation of essential oils, polyphenols, and natural pigments, whereas low temperatures may suppress release below the effective antimicrobial or antioxidant threshold. During prolonged storage, active-agent loss, pigment fading, carrier dissolution, plasticizer migration, matrix aging, and changes in crystallinity or crosslink density may progressively alter release kinetics and packaging performance. Consequently, long-term stability should be evaluated through time-resolved measurements of residual active-agent content, release behavior, biological activity, mechanical properties, and barrier performance under realistic temperature–humidity histories and intended food-contact conditions, rather than being inferred solely from initial properties or short-term tests under a single constant environment (Cui *et al.* 2024; Shen et al. 2023a; Yang et al. 2025b).

In summary, the mass transfer and controlled release processes in active packaging systems adhere to the following principles: (1) The determination of release mechanisms relies on kinetic model fitting, where Fickian diffusion applies to stable matrices driven by concentration gradients, whereas non-Fickian diffusion is accompanied by swelling, polymer chain relaxation, or carrier dissociation; (2) Environmental stimuli (pH, humidity, temperature) dynamically regulate the diffusion coefficients of active substances by altering localized physicochemical states; (3) The evaluation of controlled-release packaging relies on the quantitative correlation among release kinetic parameters, microenvironmental response characteristics, and macroscopic preservation data. Subsequent research will further establish mapping equations between structural parameters and mass transfer behaviors through the construction of multi-responsive carriers.

Comparative Performance and Applications

Performance in high-moisture systems (meat and seafood)

High-moisture food systems (meat and seafood) possess high water activity alongside abundant protein and lipid components. During refrigerated storage, these foods are susceptible to microbial proliferation, protein degradation, lipid oxidation, drip loss, and deterioration in color and odor. Active packaging for such systems must simultaneously regulate physicochemical indicators including total viable count/total bacterial count (TVC/TBC), total volatile basic nitrogen (TVB-N), thiobarbituric acid reactive substances (TBARS), pH, and color difference over the target period. Data from a meta-analysis indicate that chitosan-based preservation systems effectively reduce TVC (MD = −1.28, 95% CI [−1.52, −1.04]), coliforms (MD = −1.10, 95% CI [−1.29, −0.91]), TBARS (MD = −1.35, 95% CI [−1.53, −1.17]), and TVB-N (MD = −19.96, 95% CI [−22.56, −17.36]) in meat and seafood applications, quantitatively reflecting the comprehensive physicochemical intervention efficacy of the active packaging interface (Chen *et al.* 2025c).

In pork packaging design, the integrated use of surface microenvironment regulation, sustained release, and liquid absorption is a primary strategy. Tai *et al.* (2025) encapsulated laurel essential oil in hydroxypropyl-β-cyclodextrin (HP-β-CD) microcapsules and introduced them into active films; the microcapsule encapsulation efficiency was 83.6%, the film's DPPH and ABTS scavenging percentages were 81.5% and 40.5%, respectively, and the release of the primary active compound, 1,8-cineole, followed Fickian diffusion kinetics. When applied to fresh pork under refrigerated storage, the film maintained the TVC below 6.5 log CFU/g for 9 days while delaying weight loss, discoloration, pH increase, TVB-N, and TBARS. A fish gelatin/*Artemisia sphaerocephala*

gum–bamboo leaf flavonoid composite film developed by Liu *et al.* (2025d) was evaluated on chilled pork stored at 4 °C; relative to the control group, the FA-BLF treatment delayed increases in pH, TVC, TVB-N, and TBARS and extended shelf life from 6 to 12 days. A kenaf CNF aerogel preservation pad developed by Xiang *et al.* (2025) exhibited a density of 27.5 mg/cm³, a porosity of 96.6%, and a water absorption capacity of 3070 wt%; this structure absorbed exudates while continuously releasing cinnamon essential oil, extending the preservation period by 6 days. Jiang *et al.* (2025a) systematically compared the effects of film casting, spraying, and dipping treatments on the performance of sodium alginate edible films containing potassium sorbate. The data demonstrated that the film comprising 2% sodium alginate, 4% glycerol, and 3% potassium sorbate exhibited a tensile strength of 7.11 MPa, an EAB of 75.5%, and a WVP of 1.33 $g \cdot mm \cdot m^{-2} \cdot h^{-1} \cdot kPa^{-1}$; at the end of 14 days of preservation for fresh pork at 4 °C, the TVB-N was 2.38 mg/100 g, TBARS was 0.63 mg/kg, and TVC was 5.12 log CFU/g, outperforming the spray and dipping treatments. Wang *et al.* (2025c) reinforced chitosan active films using a Pickering emulsion ($SCCE_3$); the emulsion remained stable under extreme temperature and pH conditions for 14 days, prolonged the release period of tea tree essential oil by 4 times, and extended the shelf life of pork at 4 °C by at least 6 days. Niu *et al.* (2024) prepared a *Pleurotus ostreatus* polysaccharide-EGCG conjugate *via* free-radical grafting; in tests with chilled minced pork, the shelf life was extended to 9 days, with final TVB-N and TBARS values of 14.9 mg/100 g and 0.90 mg MDA/kg, respectively. These experiments confirm the role of film coating, multiphase sustained release, and liquid-absorbing structures in controlling high exudation and high lipid oxidation in pork.

Poultry packaging systems emphasize surface physical coverage, oxidation inhibition, and sensory maintenance. Eskandari *et al.* (2025) introduced cinnamon essential oil and *Satureja khuzestanica* essential oil nanoemulsions into chia seed mucilage films; the film's tensile strength was 60.0 MPa and elongation at break was 10.8%. At the end of 20 days of cold storage for chicken breast, the counts of aerobic mesophilic bacteria, total coliforms, and lactic acid bacteria were 8.00, 6.58, and 6.72 log CFU/g, respectively, with a pH of 6.39, TBARS of 0.63 mg MDA/kg, and TVB-N of 42.3 mg/100 g. Huda *et al.* (2025) evaluated the application of an ultrasound-assisted turmeric extract combined with a gelatin-based film in a chicken meat system; the extract exhibited antioxidant activities, including a DPPH scavenging percentage of 87 ± 7.5% and an ABTS scavenging capacity of 714.48 ± 22%. As the extract concentration increased, the film's EAB rose from 68 ± 7% to 71.9 ± 8%, while TS, solubility, moisture content, and WVP trended downward; the film inhibited lipid oxidation in minced chicken. Soufiani *et al.* (2025) encapsulated beet leaf extract into mesoporous silica nanoparticles (MSNPs) and introduced them into a chitosan/CNC composite film (formulation: 2% chitosan, 2% MSNPs, 1% CNC, and 15% extract); this system maintained various physicochemical indices within limits by controlling oxidation and microbial proliferation during an 8-day cold storage test of chicken fillets. The data indicate that composite strategies based on natural extracts, nanocarriers, and multiphase matrices can regulate the moisture resistance and release stability of poultry coating packaging.

In red meat systems such as beef, packaging design accommodates both pigment stability and oxidative flavor control. Ahmad *et al.* (2025) constructed a gelatin/CMC/chitosan ternary active film containing apple polyphenols. Optical and chemical analyses showed that the addition of polyphenols reduced the film's visible light transmittance from 60.8% to 1.8%; at a 6% polyphenol addition level, the antioxidant activity increased to 73.55 ± 0.88%. In beef packaging tests, this system inhibited the growth kinetics of TVB-

N, pH, and TBARS, extending the shelf life of beef by approximately 3 days. Experimental results suggest that interface designs with high light-blocking capacity and high reducing activity participate in color stabilization and oxidation reaction intervention in red meat systems.

Due to their high-water activity and perishability, seafood systems impose strict constraints on the anti-spoilage and gas barrier properties of active packaging materials. Targeting *Vibrio parahaemolyticus* and *Shewanella putrefaciens*, which are common and highly pathogenic bacteria in seafood, Sun *et al.* (2025a) developed a silver-hydroxyapatite functionalized chitosan (Ag-HAP@CS) composite film and quantitatively validated its preservation efficacy on *Penaeus vannamei* (Fig. 10). Physicochemical testing indicated that the hydrophobicity and water barrier capacity of the films were significantly enhanced with the addition of Ag-HAP; the optimized group, Ag-HAP20@CS, exhibited a water contact angle > 90° (Fig. 10c) and its WVP decreased to 2.25×10^{-6} g·m^{-2}·s^{-1}·Pa^{-1} (Fig. 10d). In antimicrobial kinetic assays (Figs. 10g, 10h), the film completely inactivated 10^7 CFU/mL of *V. parahaemolyticus* and *S. putrefaciens* within 2 to 4 hours, while demonstrating a UV-280 transmittance below 6% and a cell viability of 98%. During the shrimp storage test (Fig. 10e, f), the Ag-HAP20@CS film effectively delayed melanosis in the shrimp over 9 days, strictly maintaining the TVB-N below the safety threshold (≤29 mg/100 g), and suppressing the total bacterial count (TBC) and pH to below 3.90 log CFU/g and 7.52, respectively. Moreover, the Ag^+ ion migration from this system was stabilized between 0.01 and 0.10 ppm over the 9 days, which is far below the cytotoxicity threshold. In another study, Sun *et al.* (2025b) fabricated functional nanoparticles (ZCDG) from curcumin/dihydroquercetin/gum arabic and introduced them into a chitosan/gelatin film; the composite film's TS increased to 5.40 MPa, WVP and oxygen permeability decreased by 80.7% and 33.0%, respectively, and the inhibition against *E. coli* and *S. aureus* were >90%. Tests on day 8 showed that the system reduced the TVB-N of golden pompano and Pacific white shrimp by 35.8% and 26.6%, respectively, and TBARS by 79.0% and 47.8%, extending the shelf life by 6 days at 4 ± 1 °C. Addressing the exudation characteristics of fish fillets, Qiao *et al.* (2025) developed a postbiotic-loaded antibacterial absorbent pad (postbioYDFF-3) based on a matrix of gelatin, dialdehyde starch, and bacterial cellulose (3:1:0.5); its antibacterial activity increased by 65.6%, reducing the TBARS of grass carp fillets by 31.3% to 36.5% and TVB-N by 26.6%, extending the shelf life by 2 days. A photo-crosslinked chitosan methacrylate (CSMA) antibacterial hydrogel pad (degree of substitution 49.6%) constructed by Wei *et al.* (2025b) achieved long-term sustained release, with an ε-polylysine (ε-PL) loading efficiency of 98.0% and an equilibrium swelling degree of 408%; the sustained release of ε-PL was maintained for 480 min, extending the shelf life of salmon at 4 °C from 3 days to 10 days. A ZnO-MAE/CS/PLA bilayer pH-responsive film designed by Deng *et al.* (2025) utilized an inner corn starch layer for liquid absorption and an outer PLA layer for hydrophobic barrier properties, combined with mulberry anthocyanin extract and ZnO nanoparticles. At a 6% ZnO content, the film balanced mechanical strength and pH sensitivity, mitigating microbial metabolism and nutritional degradation in hairtail (*Trichiurus haumela*). These physical and biochemical tests confirm that composite pads or bilayer networks integrating moisture absorption, controlled release, and ion/pH responsiveness exert effective interfacial isolation in extremely high-moisture systems.

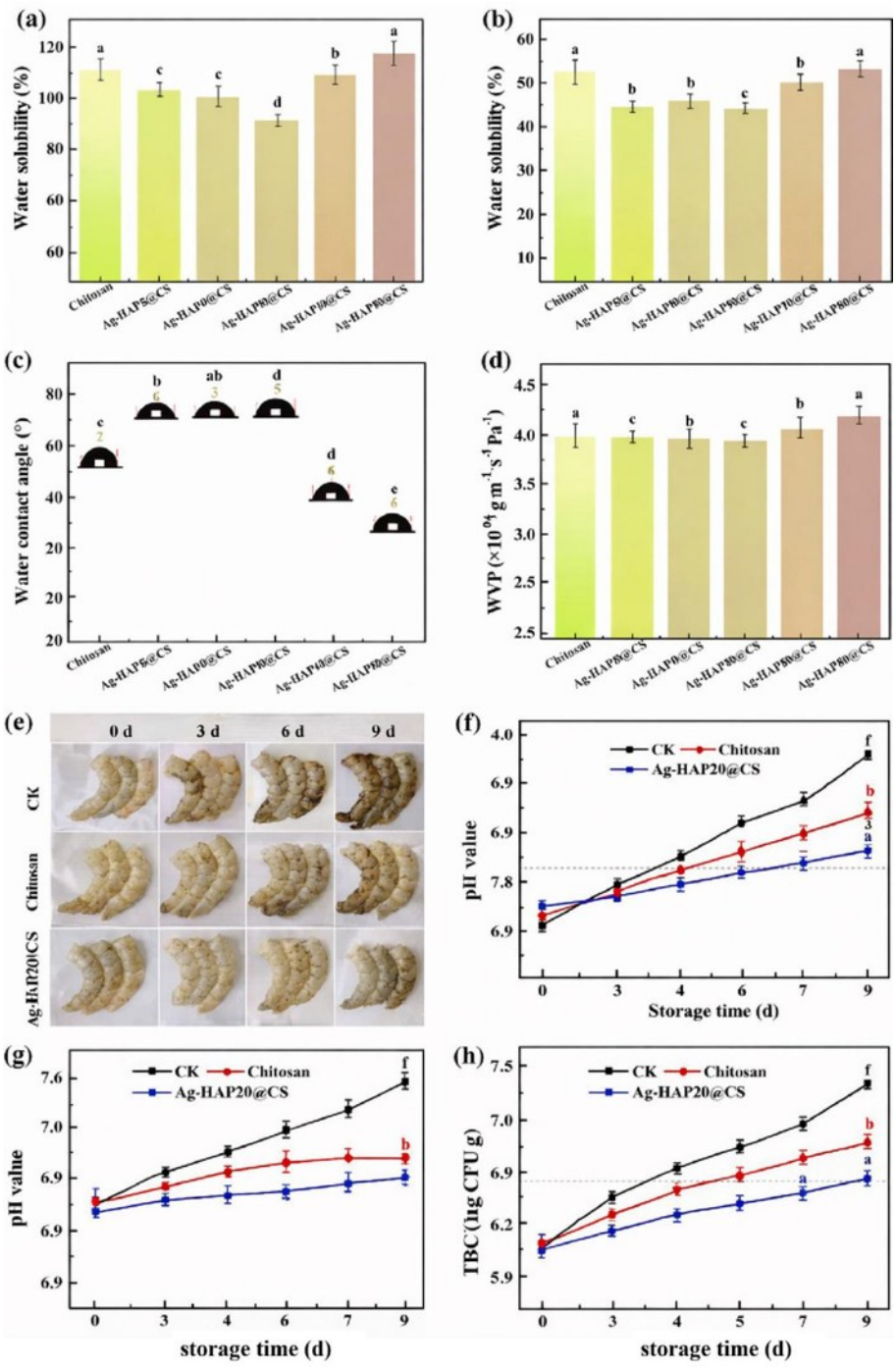

Fig. 10. Physical barrier properties of the Ag-HAP@CS film and its application evaluation in the preservation of *Penaeus vannamei*: (a) Water solubility; (b) Water absorption; (c) Water contact angle; (d) WVP; (e) Appearance evolution of the film-treated shrimp over 0–9 days; (f) pH variation of the shrimp; (g) pH changes during the antimicrobial test; (h) Inhibitory effect on the TBC of the shrimp during film treatment. Different lowercase letters indicate significant differences between groups ($P < 0.05$). (Sun *et al.* (2025a), CC BY-NC 4.0).

Synthesizing the experimental data, the application of active packaging in high-moisture food systems exhibits the following characteristic patterns: First, the intervention efficacy of the packaging interface relies on the combined contributions of antimicrobial activity, antioxidant capacity, water resistance, liquid absorption, and active-substance

release kinetics to quantitatively control deterioration indicators such as TVC, TVB-N, and TBARS in target foods. Second, specific food matrices correspond to different structural topological designs: pork and seafood systems predominantly utilize bilayer films or hydrogel pads featuring combined liquid absorption and sustained release; poultry systems are suited for uniform surface coatings; red meat packaging primarily relies on light-shielding and color-stabilizing matrices. Third, seafood systems impose the highest requirements on the wet mechanical stability and component anti-migration properties of materials; highly ionically cross-linked or hydrophobic multiphase polysaccharide substrates (*e.g.*, modified chitosan and bilayer structures) exhibit significant quality retention effects in such environments.

Performance in Respiring Systems (Fruits and Vegetables)

Postharvest quality changes in respiring foods such as fruits and vegetables are driven concurrently by respiration, water transpiration loss, ethylene release and accumulation, tissue softening, epidermal color evolution, and nutrient degradation. Active packaging targeting such systems must simultaneously regulate moisture migration, gas exchange, the ethylene microenvironment, and surface pathogen contamination to delay fruit ripening, senescence, and water loss-induced wilting. Analyses indicate that films or coatings constructed from natural polysaccharides, proteins, and plant-derived active substances can achieve preservation by reducing the weight loss rate, maintaining firmness, decelerating changes in soluble solids and titratable acidity, controlling color differences, and inhibiting fungal proliferation. The preservation efficacy of the packaging system depends on the compatibility of its hierarchical structure with the respiratory characteristics and epidermal interfacial physicochemical properties of the fruits and vegetables (Cazón *et al.* 2025).

The design of packaging systems for respiring foods is advancing toward interfacial adhesion and multifunctional integration. Addressing the engineering bottleneck where the waxy cuticle on fruit surfaces impedes uniform wetting by coating solutions, Feng *et al.* (2025) developed an amyloid-like protein (ALP) edible coating suitable for broad-spectrum fruit preservation, based on phase-transited lysozyme amyloid aggregates (Fig. 11). This system utilized phase-transited lysozyme as an interfacial adhesive layer, which, together with SA and CNC, constructed a dense physical protective network across fruit epicuticles of varying hydrophobicity. Macroscopic storage tests (Figs. 11a, 11b) demonstrated that the ALP coating exerted significant physical intervention and preservation effects on 17 types of non-climacteric and climacteric fruits, including strawberries, loquats, mangoes, bananas, and cherry tomatoes. Statistical data (Fig. 11c) showed that the coating extended the shelf life of these fruits by 2 to 5 times. Principal component analysis (PCA) of odor fingerprints (Fig. 11d) confirmed that the ALP coating effectively maintained the flavor profile of the fruits over an 8-day storage period. More importantly, based on life cycle assessment (LCA) calculations (Fig. 11e), 1 kg of ALP-coated cherry tomatoes achieved a 10-day shelf life at 23 °C, generating CO_2 emissions equivalent to only 10% of those produced by cold storage at 4 °C (which yielded a 4-day shelf life). This result quantified the engineering potential of this biomimetic interfacial coating in replacing traditional cold chain logistics and reducing carbon emissions.

Addressing the characteristics of high transpiration water loss, tissue softening, and fungal proliferation in strawberries, Rasouli *and Saba* (2025) evaluated the preservation effects of three biodegradable low-density polyethylenes (BLDPE, BLDPE/NC, and BLDPE/NM) combined with UV-C irradiation (3.2 kJ/m²) at 15 °C for 12 days. The data

demonstrated that under both the presence and absence of UV-C irradiation, the BLDPE/NC film packaging group maintained higher fruit firmness, soluble solids, titratable acidity, vitamin C, total phenolics, total anthocyanins, and total flavonoids, while exhibiting lower pH values and color difference variations. Without UV-C irradiation, the BLDPE/NC group presented the lowest decay rate and the highest total antioxidant activity; under UV-C irradiation, the BLDPE/NM group exhibited the lowest decay rate and microbial load. Additionally, the lowest weight loss rates occurred in the BLDPE and BLDPE/NC groups, whereas the weight loss rate in the BLDPE/NM group was relatively high. These tests suggest that strawberry packaging systems necessitate the establishment of a dynamic balance among gas exchange resistance, moisture retention, and surface microbial control.

The optimization of blueberry preservation systems primarily focuses on the integration of antimicrobial activity, ethylene scavenging, and microenvironmental regulation mechanisms. The CS/PVP/PVA-CEO hydrogel film prepared by Li *et al.* (2025e) exhibited optimal physicochemical, antioxidant, and antimicrobial properties when the mass fraction of CEO was 1.0 wt%. The film possessed pH-responsive release characteristics, with release kinetics conforming to a first-order kinetic model; this packaging extended the shelf life of blueberries by at least 6 days compared to the control and base film groups. Zhang *et al.* (2026) constructed a bilayer film featuring both ethylene scavenging and antibacterial functions. Its ethylene scavenger, $KMnO_4$/CuO@AZ, achieved a removal capacity of 5089.5 μg/g under a 4.5 mL initial ethylene condition; the film containing 6% of this scavenger (LE) demonstrated an ethylene scavenging capacity of 1.82 mL/m². The antibacterial layer was based on the Thy-(H_2O_2)-CS system; at an H_2O_2:CA-CS mass ratio of 1:1, the inhibition percentages against *E. coli* and *S. aureus* were 58.0% and 85.3%, respectively, increasing to 70.7% and 98.1% upon the addition of 0.5% thymol. In blueberry trials stored at 25 °C and 50% RH for 12 days, the LE film, LE/CHT composite film, and LE/CHT combined with modified atmosphere packaging (MAP) reduced internal ethylene concentrations by 99.1%, 79.5%, and 93.7%, respectively. Notably, the LE/CHT+MAP combination extended the shelf life from 4 days to 10 days. Qin *et al.* (2025) confirmed that incorporating 3 wt% Cur@SPI-SA-CS multilayer nanoparticles into pectin films improved the UV shielding rate, antibacterial capacity, and sustained release kinetics of the active molecules, extending the preservation period of blueberries to 12 days. The data indicate that the physicochemical coupling of active molecule sustained release, chemical ethylene consumption, and surface antimicrobial action is central to the anti-spoilage design for berries.

Material optimization for cherry tomato and tomato packaging primarily focuses on delaying ripening, moisture retention, and interfacial antioxidant action. Li *et al.* (2025b) introduced thyme essential oil microcapsules into a citric acid-crosslinked corn starch/konjac glucomannan matrix (MCSK4). Data demonstrated that citric acid cross-linking reduced the water vapor transmission rate of the composite film, while the addition of microcapsules enhanced the film's light shielding rate, antimicrobial efficacy, and mechanical strength. When applied to cherry tomato packaging, MCSK4 reduced the weight loss rate, maintained fruit firmness, and decelerated the degradation kinetics of total phenolics and total flavonoids. Venkatesan *et al.* (2025) incorporated Fe_3O_4 nanoparticles into a PBAT film (PF3); this film achieved a TS of 40.5 MPa, a 127.5% increase over pure PBAT. Its inhibition zones against *S. aureus* and *E. coli* were 13.5 mm and 14.7 mm, respectively, the water contact angle was 80.42°, and the oxygen and water vapor transmission rates decreased from 1085.65 to 398.55 $cc \cdot m^{-2} \cdot 24\ h^{-1}$ and from 108.20 to

40.78 $g \cdot m^{-2} \cdot 24\ h^{-1}$, respectively, extending the shelf life of cherry tomatoes from 1 day to 15 days. For standard tomatoes, Liu *et al.* (2025a) jointly introduced oregano essential oil and vanillic acid into a CMC/pectin matrix (CPOV0.06). This film exhibited a TS of 49.2 MPa, a DPPH scavenging percentage of 88.2%, an inhibition zone of 6.33 mm against *E. coli*, and completely degraded in soil within 10 days; the film extended the tomato shelf life to 21 days. Muna *et al.* (2026) applied a chitosan/HPMC layer-by-layer self-assembled coating to fresh tomatoes, comparing dipping, airbrush spraying, and manual pneumatic spraying processes. Results indicated that the airbrush spraying process exhibited the optimal film uniformity and preservation data; at the end of the 24-day storage period, the weight loss of the treated group was controlled at 7.27%, firmness was maintained at 5.44 MPa, and total soluble solids retention was approximately 68%, extending the storage life by about 12 days compared to the untreated group. Navarro-Martínez *et al.* (2025) utilized β-cyclodextrin-encapsulated thymol/eugenol to prepare active paper inserts, which significantly reduced the populations of Enterobacteriaceae and molds on the surface of cherry tomatoes, while inhibiting the proliferation of psychrotrophic bacteria and molds in kale. Studies confirm the intervention effects of enhanced physical barriers, moisture balance regulation, and active release kinetics on maintaining the quality of tomato-type fruits.

The packaging of climacteric fruits such as bananas aims at delaying the respiratory climacteric peak and suppress moisture loss. The SA/NCFs/CS composite edible coating prepared by Yu *et al.* (2025) formed a three-dimensional stable network *via* hydrogen bonding, ester bonds, and electrostatic interactions. The coating exhibited an EAB of 101%, a TS of 88.9 MPa, and a toughness of 6.59 MJ/m^3; *in vitro* assays determined its antioxidant activity at 96.3% and antimicrobial effectiveness at 99.02%. At 4 °C, the coating extended the shelf life of bananas to 12 days, and under variable temperature conditions (25/4 °C), the preservation period reached 12 to 14 days. Weng *et al.* (2026) evaluated spray coating formulations based on gum arabic (GA), gelatin (GE), soy protein isolate (MPI), and blended oil (CO). The optimized formulations (5% GA, 4% MPI, 1% CO and 4% GE, 2% MPI, 4% CO) exhibited surface contact angles distributed between 31.1° and 67.7°; in a 10-day storage test, they reduced the water loss of the fruits and decelerated the peel browning and flesh softening processes. Al-Yahyai *et al.* (2025) analyzed the physical intervention of olive oil and moringa oil coatings on banana quality under different temperatures. The untreated group had an average weight loss of 6.23%, whereas the moringa oil and olive oil treatment groups decreased to 5.29% and 5.28%, respectively; the average firmness increased from 3.18 kgf in the control group to 4.14 kgf and 4.02 kgf. In a 15 °C environment, the average weight loss dropped to 4.47%, lower than the 6.73% observed at 25 °C. In cultivar-specific tests, the weight loss of Milk banana and Cavendish at 15 °C decreased by 33.0% and 34.3%, respectively; the weight loss percentages of Cavendish treated with moringa oil and olive oil were reduced by 13.4% and 18.3%, respectively. The data indicate a thermodynamic interaction between the water vapor barrier properties of the coating and the environmental temperature, which directly impacts the surface transpiration kinetics of climacteric fruits.

Addressing the susceptibility of fresh-cut apples to browning and high-water loss rates post-cutting injury, Ali *et al.* (2025) formulated an active coating composed of 1.5% chitosan, 2% ascorbic acid, and 2% citric acid, independently loaded with different concentrations of oregano essential oil (0.06% or 0.15%) or cinnamon leaf essential oil (0.06% or 0.1%). In assays conducted over 9 days of storage at 4 °C, the coating containing 0.1% cinnamon leaf essential oil reduced the water activity of the slices from 0.910 in the

control group to 0.894. In addition, the coating maintained a firmness of 24.5 N (compared to 22.5 N for the chitosan-only treatment group); the chromaticity parameter a value was 1.07 (*versus* 4.22 for the control), quantitatively reflecting a reduction in epidermal browning. Biochemical analyses revealed that this coating system reduced polyphenol oxidase (PPO) activity and maintained surface microbial stability. Experimental data indicate that the packaging mechanisms for inhibiting browning in fresh-cut fruits encompass the combined suppression of moisture migration, enzymatic reactions, and surface microbial growth.

In the non-contact packaging application of fresh-cut leafy greens, Ye *et al.* (2026) applied 2% peppermint essential oil to the inner surface of packaging boxes to construct a volatile active layer system. During 8 days of storage at 4 °C, this treatment decelerated the browning rate at the cut edges of fresh-cut lettuce and reduced the overall respiration intensity and ethylene release. Compared to the control group, the active layer treatment group exhibited lower total counts of bacteria, yeasts, and molds, inhibited PPO and phenylalanine ammonia-lyase (PAL) activities, an increased retention rate of cell membrane integrity, and a deceleration in the biochemical degradation of chlorophyll. This non-contact gas diffusion mechanism acts on the leaf tissue *via* the gas-liquid partition equilibrium in the headspace, circumventing localized high concentrations or physically migrated flavor residues caused by direct contact with the active components.

Mushrooms, representing a high respiratory intensity system, are prone to enzymatic browning, moisture loss, and physical tissue collapse postharvest. NeysariFam *et al.* (2025) prepared potato starch/guar gum/nanoclay/pine needle essential oil bionanocomposite films and applied them to *Agaricus bisporus* mushrooms in combination with modified atmosphere packaging (MAP) technology. The study compared MAP1 (10% O_2, 15% CO_2, N_2 balance), MAP2 (15% O_2, 10% CO_2, N_2 balance), and ambient air conditions over a 15-day test period. In the unpackaged group, firmness, ascorbic acid, protein, and total phenolic contents decreased by 76.1%, 66.5%, 77.6%, and 72.7%, respectively, at the end of storage. When treated with the nanocomposite film combined with MAP1, the declines in these biochemical and physical indicators were controlled at 32.7%, 35.2%, 36.0%, and 35.7%, extending the system's shelf life to 15 days. The data confirm that adjusting the O_2/CO_2 partial pressures in the packaging headspace, establishing physical barriers against moisture migration, and the controlled release of volatile active components can systematically intervene in the postharvest metabolic deterioration rate of high-respiring tissues.

Synthesizing physicochemical experiments and preservation data, the application of active packaging in respiring food systems exhibits distinct physicochemical intervention patterns: First, because of the physiological and metabolic characteristics of fruit and vegetable tissues, the performance evaluation system of packaging systems relies on the macroscopic measurement of weight loss values, firmness decay kinetics, color evolution, changes in soluble solids and titratable acidity concentrations, headspace ethylene partial pressures, and respiration rates (Cazón *et al.* 2025). Second, the heterogeneous physiological characteristics of fruits and vegetables dictate the need for specific matrix architectures: berries favor flexible films or coatings that provide moisture constraints, localized release of antimicrobial agents, and high interfacial adhesion; climacteric fruits such as tomatoes and bananas rely on the packaging matrix for chemical ethylene scavenging and the regulation of gas-liquid exchange mass transfer resistance.

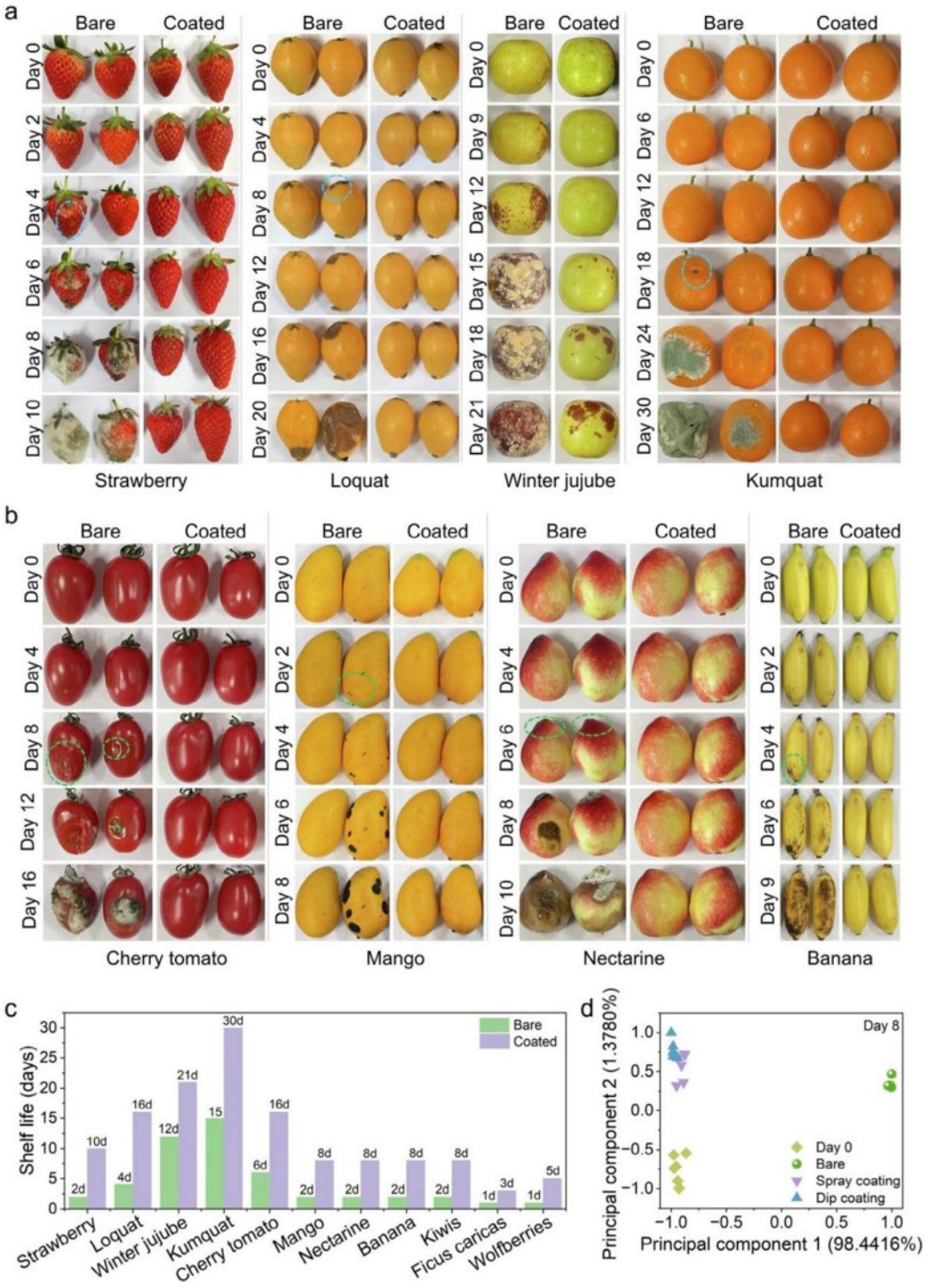

Fig. 11. Preservation efficacy and environmental impact assessment of the ALP coating on respiring foods (broad-spectrum fruits and vegetables): (a) Comparison of the appearance preservation effect of the coating on non-climacteric fruits (strawberry, loquat, winter jujube, kumquat); (b) Comparison of the appearance preservation effect of the coating on climacteric fruits (cherry tomato, mango, nectarine, banana); (c) Shelf life statistics of bare and coated fruits; (d) Principal component analysis of fruit odor fingerprints at the end of storage; (e) Comparison of carbon emissions (kg CO_2-eq) between 23 °C coated storage and 4 °C cold storage based on LCA. (Reproduced from Feng *et al.* (2025), CC BY-NC-ND 4.0).

For high respiratory metabolism and mechanically injured systems such as mushrooms and fresh-cut vegetables, the physical coupling of MAP gas ratio control, non-contact surface volatile active layers, and anti-transpiration coatings delays lipid oxidation and enzymatic browning processes (Li *et al.* 2025e; Rasouli and Saba 2025; Zhang *et al.* 2026). Third, effective active packaging must integrate multiple interfacial functions—inhibiting water transpiration, regulating gas permeation fluxes, photocatalytically or adsorptively scavenging ethylene, and releasing antimicrobial and antioxidant molecules—within a single substrate network to establish quantitative intervention mechanisms that suppress the complex respiratory metabolism of fruits and vegetables.

Performance in Low-Moisture and Lipid-Rich Systems (Bakery, Dairy, and Snack Foods)

Quality deterioration in low-moisture and lipid-rich food systems is driven by three coupled pathways: fungal proliferation on porous bakery surfaces, moisture migration-induced textural (crispness) collapse, and cumulative lipid autooxidation. Active packaging design parameters for such commodities shift from direct interfacial antimicrobial contact to headspace-mediated volatile release, strict oxygen exclusion, and humidity-tolerant barrier preservation. For cereal-based snacks and baked products, increases in ambient relative humidity not only accelerate moisture uptake and loss of crispness but concurrently diminish the oxygen barrier efficacy of hydrophilic biopolymer networks (Noshirvani *et al.* 2024).

In bakery applications, recent active packaging interventions primarily rely on vapor-phase antifungal regulation rather than direct surface coating. Noshirvani *et al.* (2024) fabricated fully biobased films composed of carboxymethyl cellulose, chitosan, and oleic acid containing cinnamon or ginger essential oils. In the bread trials, slices were sandwiched between active films, sealed in polyethylene bags, and stored at 25 °C. Bread wrapped with the control film showed fungal growth after 7 days; the highest ginger-oil formulation delayed visible growth to 28 days, whereas the highest cinnamon-oil formulations maintained complete inhibition for 60 days. In the direct-coating test at 25 °C, the highest cinnamon-oil formulation also maintained zero yeast and mold counts through day 15. Fan *et al.* (2024) constructed a corn starch-based composite film infused with clove essential oil nanoemulsion, validating the efficacy of non-contact application modes during a 15-day non-contact bread storage test, with the 40% nanoemulsion film exhibiting optimal preservation performance. For sweet baked goods, Singh *et al.* (2024) prepared PLA films loaded with *Trachyspermum ammi* essential oil (as an antimicrobial agent) and vanilla oil (as an aroma corrector). At a 50 wt% essential oil blend concentration, the shelf life of waffles was extended from 2 days (neat PLA film) to 30 days. The introduction of vanilla oil indicates that the practical performance of essential-oil-based packaging depends not only on vapor-phase antimicrobial efficacy, but also on maintaining an aroma profile compatible with the packaged food. Strongly aromatic essential oils may inhibit fungal growth while simultaneously altering product odor or flavor, particularly when high loadings are required. Therefore, the active-agent concentration and release rate should be optimized within both the antimicrobial-effective range and the sensory-acceptable range. However, most bakery-packaging studies currently emphasize microbial counts and visible fungal growth, whereas systematic evaluation of odor, taste, appearance, texture, and consumer acceptance remains comparatively limited.

For dry, lipid-rich matrices, oxidative stability supersedes microbial inhibition as the core design objective. Zhai *et al.* (2025) prepared extrusion-blown PBAT/TPS active films containing grape seed extract (GSE) for peanut butter packaging. In the storage test, 25 g portions were vacuum-packaged in commercially available LDPE, PBAT/TPS/GSE-0, or PBAT/TPS/GSE-5 films, with unpackaged samples as controls, and stored at 23 °C. The unpackaged peanut butter reached or exceeded the peroxide safety threshold after 150 days, whereas peanut butter packaged with PBAT/TPS/GSE-5 reached the threshold only at 300 days. After 300 days of storage, the acid value of the PBAT/TPS/GSE-5 packaged group was 1.11 $mg \cdot g^{-1}$, significantly lower than the LDPE group (1.60 $mg \cdot g^{-1}$) and unpackaged controls (1.69 $mg \cdot g^{-1}$), with an estimated shelf life exceeding 300 days. Turan *et al.* (2024) formulated a gelatin-based edible active coating utilizing coffee by-product cascara for roasted hazelnuts. The optimized formulation (5.1% gelatin, 89.2% extract, 5.7% glycerol) exhibited maximal oxygen barrier capacity; accelerated shelf-life tests at 35 and 45 °C indicated the coating doubled the hazelnut shelf life. Test results confirm that the preservation of nut and spread products relies on the combined physicochemical contributions of long-term oxygen exclusion and interfacial antioxidant activity.

Preservation of dairy matrices encompasses the synchronous intervention of microbial proliferation, surface dehydration, light-sensitive degradation, and lipid oxidation. Bruni *et al.* (2024) designed PHBV-based antimicrobial packaging incorporating lauroyl arginate ethyl (LAE) for cheese preservation, determining minimum inhibitory concentrations (MIC) of 25 to 100 ppm against spoilage and pathogenic microorganisms. Active coating technology exhibited higher processing retention than bulk incorporation (4% LAE loss *via* coating *versus* 50% *via* bulk incorporation). In release tests, the coated PHBV system released 43% of LAE into 50% ethanol (food simulant D1) over 10 days at 20 °C; in processed-cheese trials, the LAE-coated PHBV packaging showed preservation efficacy comparable to modified-atmosphere packaging. Sharma *et al.* (2025b) developed PLA/PBAT/TiO_2 composite films loaded with eucalyptus essential oil for cheese packaging; the 10 wt% eucalyptus formulation completely inhibited *E. coli* growth, increased biofilm inhibition from 21% to 92%, reduced UV transmittance at 280 nm to 0.00%, and limited the cheese weight loss to 1.47% over 12 days (compared to 9.30% for the control). Torres *et al.* (2025) prepared a sustained-release chitosan/starch film containing 1.5% rosemary essential oil for fresh cheese. This formulation increased film elasticity by 12%, improved water-vapor barrier performance by 75%, produced inhibition zones of 19.50 ± 0.50 mm, exhibited Fickian release kinetics, and extended the shelf life of refrigerated cheese by 12 days. These data characterize dairy packaging as a multifunctional integrated platform encompassing antimicrobial action, barrier properties, and controlled release.

From a structural design perspective, the technical bottleneck for high-fat and low-moisture matrices lies not merely in active agent loading but in the barrier integrity of films under high-humidity conditions. Karkhanis *et al.* (2021) confirmed that crackers packaged in neat PLA and PLA/CNC films remained shelf-stable below 50% RH at 25 °C; at RH > 50%, the CNC-incorporated composite films extended shelf life by approximately 40% compared to neat PLA. Concurrently, renewable nanostructured multilayer packaging developed by Pasquier *et al.* (2022) demonstrated that physical coupling between functional layers effectively mitigates the long-standing trade-off between oxygen exclusion and water-vapor resistance in bio-based films. Consequently, the development of active packaging systems for bakery, snack, nut, and dairy matrices relies on the design of multilayer or nanocomposite architectures, wherein volatile release, oxygen shielding,

and humidity tolerance are quantitatively and synchronously optimized according to the specific deterioration pathways of the target food.

Regulatory Compliance, Environmental Fate, and Industrial Scalability

Migration limits and food contact regulatory compliance

The safety evaluation of biodegradable active packaging is independent of the material's biodegradability or the natural origin of its active components; its core lies in assessing the over-limit migration of substances, the release of non-intentionally added substances (NIAS) during contact, and the potential impact of these processes on the physicochemical properties, sensory quality of the food, and consumer health. Active packaging systems frequently incorporate functional components such as essential oils, polyphenols, antimicrobial peptides, inorganic nanoparticles, or metal-organic frameworks (MOFs), which increase the physicochemical dimensions of their safety evaluation. Spinei and Oroian (2025) indicated that the migration process at the interface of bio-based or biodegradable packaging is governed by thermodynamic partition and kinetic diffusion. This process is jointly regulated by the characteristics of the food matrix, contact time, temperature and humidity, penetrant polarity, polymer topological structure, and additive concentration. Current studies indicate that nanoparticles are typical intentionally added migrants, whereas oligomers and reaction by-products derived from polymer degradation constitute the primary sources of NIAS (Spinei and Oroian 2025). Toxicological assessments of inorganic nanoparticles suggest that long-term exposure effects and migration mechanisms in real food systems require further quantitative data support. Importantly, total elemental migration does not necessarily distinguish intact nanoparticles from dissolved ions, although these forms may differ in bioavailability and toxicological effects. Nanomaterial assessment should therefore consider particle size, surface chemistry, aggregation and dissolution behavior, polymer–particle interactions, and the intended time–temperature conditions of food contact. Authorization of a substance in its conventional bulk form should not be assumed to automatically cover its nanoform, which may require a separate exposure and risk assessment. Therefore, the safety evaluation of packaging systems must rely on a systematic framework of "regulatory limits–migration testing–risk assessment" (Wang *et al.* 2025d).

Within the regulatory framework for food contact materials (FCMs), the European Union system has established comprehensive evaluation standards. According to the framework principles of Regulation (EC) No 1935/2004, under normal or foreseeable conditions of use, FCMs must not transfer their constituents to food in quantities that could endanger human health, nor bring about an unacceptable change in the composition or sensory characteristics of the food. Furthermore, Commission Regulation (EC) No 2023/2006 establishes good manufacturing practices (GMP), requiring that the production process possess a sound quality assurance and control system and a traceable raw material selection mechanism (Amirullah *et al.* 2024; Thapliyal *et al.* 2024). For plastics and their composite materials, Commission Regulation (EU) No 10/2011 establishes a Union List of authorized substances and specific migration limits (SMLs), and specifies standardized food simulants and testing conditions. This regulation sets an overall migration limit (OML) of 10 mg/dm², which, converted using the conventional surface area-to-mass ratio of 6 dm²/kg, is equivalent to 60 mg/kg of food (Amirullah *et al.* 2024; Gupta *et al.* 2024). The regulation designates 3% (w/v) acetic acid as the simulant for acidic foods and requires that migration tests be executed under parameters reflecting the most severe foreseeable

conditions of use; compliance must be demonstrated by a Declaration of Compliance (DoC) and corresponding technical documentation.

Active and intelligent packaging systems are additionally subject to Commission Regulation (EC) No 450/2009, particularly when the packaging is designed to release active substances, absorb undesirable compounds, or provide information on food condition. This regulation requires that active and intelligent functions do not conceal food deterioration or mislead consumers, and that intentionally released substances comply with the relevant food legislation. In the United States, food-contact substances may be regulated through applicable provisions of Title 21 of the Code of Federal Regulations, an effective Food Contact Substance Notification, or, where appropriate, a Threshold of Regulation exemption. Because these regulatory pathways are linked to the identity of the substance, intended use, food type, contact temperature and duration, migration level, and dietary exposure, authorization of an individual component cannot be directly extended to the complete composite packaging system. Accordingly, plasticizers, crosslinkers, active agents, nanomaterials, carriers, and processing- or degradation-derived non-intentionally added substances should be evaluated together under the intended food-contact conditions.

Active and intelligent packaging, functioning by releasing substances into or absorbing substances from the food or its surrounding environment, possesses non-inert characteristics and is subject to Commission Regulation (EC) No 450/2009 (Amirullah *et al.* 2024). Under this regulation, actively released substances are legally defined as food ingredients and must comply with relevant food legislation and labeling requirements (Narayana *et al.* 2025). Consequently, the compliance evaluation of release-type active packaging must verify the legality of the release behavior, the food-grade nature of the released substances, the migration levels of non-active components, and establish a complete traceable documentation system (Narayana *et al.* 2025).

The United States regulatory system implements management through multiple pathways, including Food Contact Substance Notification (FCN), substances listed in Title 21 of the Code of Federal Regulations (21 CFR), and Threshold of Regulation (TOR) exemptions (Nerin *et al.* 2025). According to the provisions of 21 CFR 170.39, if the dietary concentration resulting from a food contact substance is not greater than 0.5 ppb (corresponding to an exposure of ≤ 1.5 μg/person/day), and it presents no carcinogenic risk, exerts no technical effect on the food, and has no significant environmental impact, it may be exempted from regulation as a food additive (Panou and Karabagias 2024). This provision requires the submission of validated migration data under the most severe conditions of use, residual levels, and the corresponding analytical methods and limits of detection (Panou and Karabagias 2024). Quantitative migration data serve as the fundamental technical basis for assessing the market entry compliance of active packaging systems.

The migration behavior of active packaging containing essential oils and natural extracts exhibits a high degree of system dependence. Pei *et al.* (2025) systematically analyzed the migration characteristics of thyme, cinnamon, and lemon essential oils from chitosan films into various food simulants (distilled water, 3% acetic acid, 10% ethanol, 50% ethanol, and 95% ethanol). The data demonstrated that cinnamon essential oil exhibited a higher partition coefficient and solubility in 50% ethanol; the solubility of lemon essential oil increased with ethanol concentration; whereas 3% acetic acid induced the structural dissociation of the chitosan film, accelerating matrix swelling and essential oil migration release. The study indicated a positive correlation between the amount of essential oil migration and matrix solubility, and a negative correlation with the degree of

swelling in 95% ethanol. These results signify that the migration of natural active substances is co-controlled by their solubility in the simulant, the swelling/degradation kinetics of the polymer, and the evolution of the interfacial physicochemical structure, leading some hydrophilic stable films to exhibit accelerated release behaviors in high-ethanol or acidic media.

Targeted material topological design can control the migration of active components within regulatory limits. Olewnik-Kruszkowska *et al.* (2025) prepared PLA–PEG films individually loaded with clove, grapefruit, rosemary, and tea tree oils; the introduction of essential oils improved elongation at break and UV shielding rates, with the clove and tea tree oil systems reducing the water vapor transmission rate (WVTR) by approximately 1.0 g/(m²·h). Migration tests revealed that the migration levels of components from clove, grapefruit, and tea tree oils into the acetic acid simulant were all below 10 mg/kg, complying with the EU's overall migration limit requirements. Sam *et al.* (2025) constructed a paper-based active coating based on essential oil Pickering emulsions stabilized by cationic cellulose nanofibers (cCNF). This coating exhibited a DPPH radical scavenging percentage of 92% and inhibition of 99.99% and 99% against *Listeria monocytogenes* and *E. coli*, respectively; across three standard simulants, its specific migration levels remained low. This demonstrates that the compliance of active substance-releasing packaging primarily depends on the carrier structure, dispersion state, and thermodynamic compatibility between the polymer and the contact medium.

Non-intentionally added substances (NIAS) generated from biodegradable polymer matrices and their blending systems also pose potential migration risks. Wongphan *et al.* (2025) conducted migration screening on TPS/PBAT packaging, utilizing 95% ethanol, 10% ethanol, and 3% acetic acid as simulants at 60 °C for 10 days. No substances exceeding the limits were detected in 3% acetic acid and 10% ethanol; however, new compounds formed *via* the reaction of PBAT monomers/oligomers with the simulant were detected in 95% ethanol (at concentrations below the regulatory limits). Ashraf *et al.* (2026a) quantified the NIAS migration patterns in PBS, PLA, and their blended films. Tests were conducted in 10% and 50% ethanol (treated at 20 °C and 40 °C for 10 days, and 70 °C for 2 h). Analyses indicated that the concentration of volatile organic compounds (VOCs) released from the PBS/PLA blended films was higher than that from the single-component films, and the release of oligomers was significantly driven by the polar medium and temperature. Although all tested samples met the EU overall migration limits, the study noted that the safety evaluation of biodegradable matrices requires detailed substance migration profiling analysis. Consequently, NIAS such as oligomers generated from polymer depolymerization, degradation by-products, and processing residues should be incorporated into a comprehensive compliance assessment model.

Regulatory assessments exhibit a high degree of specificity for composite active packaging doped with inorganic nanoparticles. A systematic review by Wang *et al.* (2025d) noted that while Ag, CuO, ZnO, and TiO_2 nanoparticles enhance the mechanical and barrier properties of materials, their potential migration may induce oxidative stress responses and cytotoxicity in target foods, and current analytical technologies present sensitivity gaps in distinguishing between particulate and ionic migration. At the regulatory level, Annex II of EU 10/2011 enforces strict limits on specific elements: for example, the SML for Zn is 5 mg/kg, Ni is 0.02 mg/kg, and Co is 0.05 mg/kg. For primary aromatic amines (PAAs) without established specific migration limits, the regulation mandates that the monomer detection limit must not exceed 0.002 mg/kg, and the total PAA concentration must not exceed 0.01 mg/kg. In quantitative experiments, Joseph and Sathianathan (2025) utilized

inductively coupled plasma mass spectrometry (ICP-MS) to determine the migration levels of ZnO nanoparticle/PVA composite films, calculating a nanoparticle diffusion coefficient of 5.02×10^{-13} m²/s and a zeta potential of −7.49 mV; the results confirmed that the migration amount of this composite system in the fatty food simulant was below the safety threshold. These data indicate that the compliance of nanoparticle composite materials is condition-dependent and necessitates independent evaluation tailored to specific formulations and application scenarios.

In summary, migration limits and compliance evaluations constitute boundary constraints for the design of biodegradable active packaging. The engineering translation of material systems relies on verification across four dimensions: (1) the composition of the material and the selection of active substances must follow clear regulatory pathways (*e.g.*, distinguishing among conventional FCMs, active FCMs, and the U.S. FCS/TOR exemption systems); (2) migration testing must be conducted using appropriate food simulants under time and temperature conditions representing the most severe foreseeable conditions of use; (3) the detection targets must concurrently cover added substances such as IAS and NIAS derived from polymer degradation or cross-linking; and (4) nanomaterials and release-type systems must be supported by exposure assessment data and DoC. The physicochemical efficacy of the active functions and compliance with migration requirements jointly determine the feasibility of translating these composite packaging systems into industrial applications.

Biodegradation behavior and life cycle considerations

In active packaging systems, "biodegradability" is not an unconditional intrinsic property, nor is its degradation rate constant across all environments. Rather, it is a kinetic process highly coupled with environmental parameters, material microstructures, and end-of-life disposal routes. The assessment of degradation behavior necessitates the quantification of the rate, mechanism, and extent of material degradation in real-world environments, combined with LCA to quantify the overall environmental burden. Regulatory agencies (such as the Washington State Department of Ecology) explicitly state that "compostable" products must meet scientific standards under specific industrial composting conditions (*e.g.*, ASTM D6400, D6868, D8410, ISO 17088, or EN 13432). Literature reviews on composting technologies for biodegradable packaging indicate that industrial composting systems differ fundamentally from open natural environments in terms of temperature, humidity, aeration efficiency, and microbial communities; therefore, the "industrially compostable" attribute cannot be directly equated with ubiquitous rapid degradation in natural environments (Silvee 2026).

Additives, crosslinkers, and nanofillers can alter biodegradation in opposite directions by changing water uptake, polymer-chain mobility, porosity, and microbial accessibility. Hydrophilic or readily degradable additives may accelerate water penetration and mass loss, whereas hydrophobic active agents and dense crosslinked networks generally restrict swelling and enzyme access, thereby delaying degradation. Nanofillers may retard degradation by increasing matrix compactness, crystallinity, and transport-path tortuosity, but particle-induced defects or catalytic activity may also promote chain scission and fragmentation. For inorganic nanomaterials, film disintegration or mass loss should not be equated with complete mineralization because persistent particles or ionic residues may remain. Consequently, degradation should be evaluated for the complete formulation under a defined end-of-life environment rather than inferred from the neat biopolymer matrix alone.

Recent empirical studies demonstrate specific patterns in the environmental degradation kinetics of biodegradable active packaging: accelerated degradation is observed in soil and compost environments, whereas degradation is retarded in aquatic and marine environments. Westlake *et al.* (2025) analyzed the degradation profiles of gallic acid-loaded vanillin cross-linked chitosan films across multiple environments. The material exhibited a mass loss rate exceeding 90% within 12 weeks in soil, achieving complete degradation at 24 weeks. Over the same 12-week period, the mass loss rates in seawater and freshwater were only 43.1±6.7% and 32.6±0.9%, respectively. Thermodynamic analysis revealed that the glass transition temperature (T_g) of the material decreased from an initial 274 to 215 °C, while the total organic carbon (TOC) content in the soil increased from 18.2±0.5% to 25.1±0.8%. The variations in physicochemical indicators demonstrated that the physical fragmentation of the material in soil was accompanied by polymer backbone cleavage and the transfer of organic carbon to the environmental matrix. Furthermore, the mass loss rate of the material over 24 weeks was 34.1±1.6% in sterilized soil, 63.6±1.6% in home compost bins, and 35±7.9% in an open outdoor environment. The data confirm that microbial activity, moisture content, and fluctuations in environmental conditions co-determine the ultimate degradation kinetics, while polymer cross-linking density and active substance release behaviors significantly alter the environmental fate.

The introduction of active components and the topological design of network structures, while enhancing the physical properties of packaging, may generate a competing effect that retards environmental degradation. Teleky *et al.* (2025) prepared a multifunctional active film comprising PVOH/itaconic acid/chitosan/lemon peel extract/silver nanoparticles. This film achieved a maximum soil degradation of 61.8% over 8 weeks and significantly reduced the weight loss of blueberries during an 11-day preservation test at 4 °C, reflecting a balance between service-life stability and end-of-life degradability. Haddar *et al.* (2025) quantified this "performance-degradation" coupling relationship in levan/chitosan composite films. The L25:C75 formulation exhibited a tensile strength of 15.43 ± 0.04 MPa, an elongation at break of 35.37 ± 1.12%, an $ABTS^{\bullet+}$ scavenging percentage of 91%, and inhibition zones of 18 ± 0.30 mm and 16 ± 0.20 mm against *E. coli* and *S. aureus*, respectively. However, after 14 days of soil burial, the L75:C25 sample with a higher levan ratio reached a degradation rate of 68%. When the L25:C75 film was applied to beef packaging at 4 °C for 7 days, it reduced the total viable count by 1.8 log CFU/g compared to the LDPE control. Experimental data confirms an inherent restrictive relationship between the enhancement of material properties (*e.g.*, increased cross-linking, improved water resistance, and the introduction of antimicrobial agents) and terminal environmental degradation kinetics.

The design of biomimetic hierarchical structures provides an engineering pathway to decouple the competing relationship between barrier performance and rapid degradation. Dhatt *et al.* (2025) developed a biomimetic layered, ecological, advanced, multi-functional film (LEAFF) composed of a CNF core, a PLA coating, and a hexamethylene diisocyanate crosslinker (Fig. 12). While exhibiting high transparency and applicability for food packaging (Fig. 12A), the LEAFF system enabled the rapid degradation of PLA-based matrices in ambient temperature soil. Macroscopic degradation monitoring (Figs. 12B, 12C) demonstrated that under soil conditions at 25 °C and 40% to 60% RH, the LEAFF membrane completely degraded within 5 weeks, whereas pure PLA films exhibited no significant mass loss (Fig. 12E). Microstructural and metagenomic analyses (Figs. 12D, 12F) revealed that the hierarchical structure and the colocalization of the CNF energy

source fostered a highly diverse microbial microenvironment (*e.g.*, increased relative abundance of specific genera such as *Planctoellipticum* and *Streptomyces*), which physically and metabolically facilitated the breakdown of the recalcitrant PLA layer. Concurrent physical testing indicated that the oxygen transmission rate (OTR) of the LEAFF film was 0.772 $cm^3 \cdot m^{-2} \cdot day^{-1} \cdot atm^{-1}$, compared to 108.5 $cm^3 \cdot m^{-2} \cdot day^{-1} \cdot atm^{-1}$ for the pure PLA film. These data demonstrate that multi-layer structural assembly, interfacial compatibilization, and microenvironment modulation can concurrently optimize chemical stability during the service period and rapid biodegradation during the disposal phase.

Life cycle assessment of materials expands the analytical boundary from simple degradation kinetics to systemic environmental impacts. Hasan *et al.* (2025) conducted a cradle-to-grave LCA on PBAT-talc agricultural films, identifying raw material preparation, film blowing, and the composting phase as primary environmental hotspots. The study noted that increasing the proportion of bio-based raw materials and adopting a cleaner energy matrix could further reduce the total environmental burden. Akbarian-Saravi *et al.* (2025) provided quantitative LCA data for PBAT resin blends: based on gate-to-gate and screening-level end-of-life assessments, the production of 1.0 kg of PBAT blend generated a total environmental burden of approximately 921 mPt and a global warming potential (GWP) of 8.66 kg CO_2-eq. In the end-of-life scenario analysis, the composting of PBAT yielded an emission reduction benefit of approximately 10.7 kg CO_2-eq compared to PE landfilling, reducing the net environmental impact to −53.9 mPt; in contrast, PE landfilling corresponded to 288.8 mPt and 2.2 kg CO_2-eq. The calculations demonstrate that the LCA metrics of biodegradable packaging are systematically governed by upstream resin synthesis, filler modification, processing energy consumption, and end-of-life disposal methods.

Compared with conventional petroleum-based plastics, biodegradable packaging does not necessarily have a lower environmental burden under all conditions. Its potential advantages include reduced dependence on fossil resources and compatibility with biological end-of-life routes, whereas raw-material preparation, polymer modification, drying, filler production, and inadequate composting infrastructure may increase its life-cycle impacts. Conventional plastics benefit from mature high-throughput processing and established recycling routes in some regions. However, they remain dependent on fossil feedstocks and may persist under inappropriate disposal conditions. Therefore, comparative LCA should use a functionally equivalent unit, such as the amount of packaging required to preserve the same quantity of food for the same storage period, rather than comparing equal material masses alone. Avoided food loss and realistic regional end-of-life infrastructure should also be included. Consequently, the environmental advantage of biodegradable packaging may be substantial under appropriate collection and composting conditions, but the advantage may be diminished or reversed when such infrastructure is unavailable or when equivalent preservation performance is not achieved (Bilal *et al*. 2025; Kegl *et al*. 2025).

Recent literature reviews establish a condition-dependent relationship between the "bio-based/biodegradable" attributes and "low environmental impact." Bilal *et al.* (2025) noted that sustainability evaluation models for food packaging must concurrently integrate raw material sourcing, manufacturing energy consumption, recycling/composting infrastructure compatibility, and the linked carbon offset effects generated by reducing food waste.

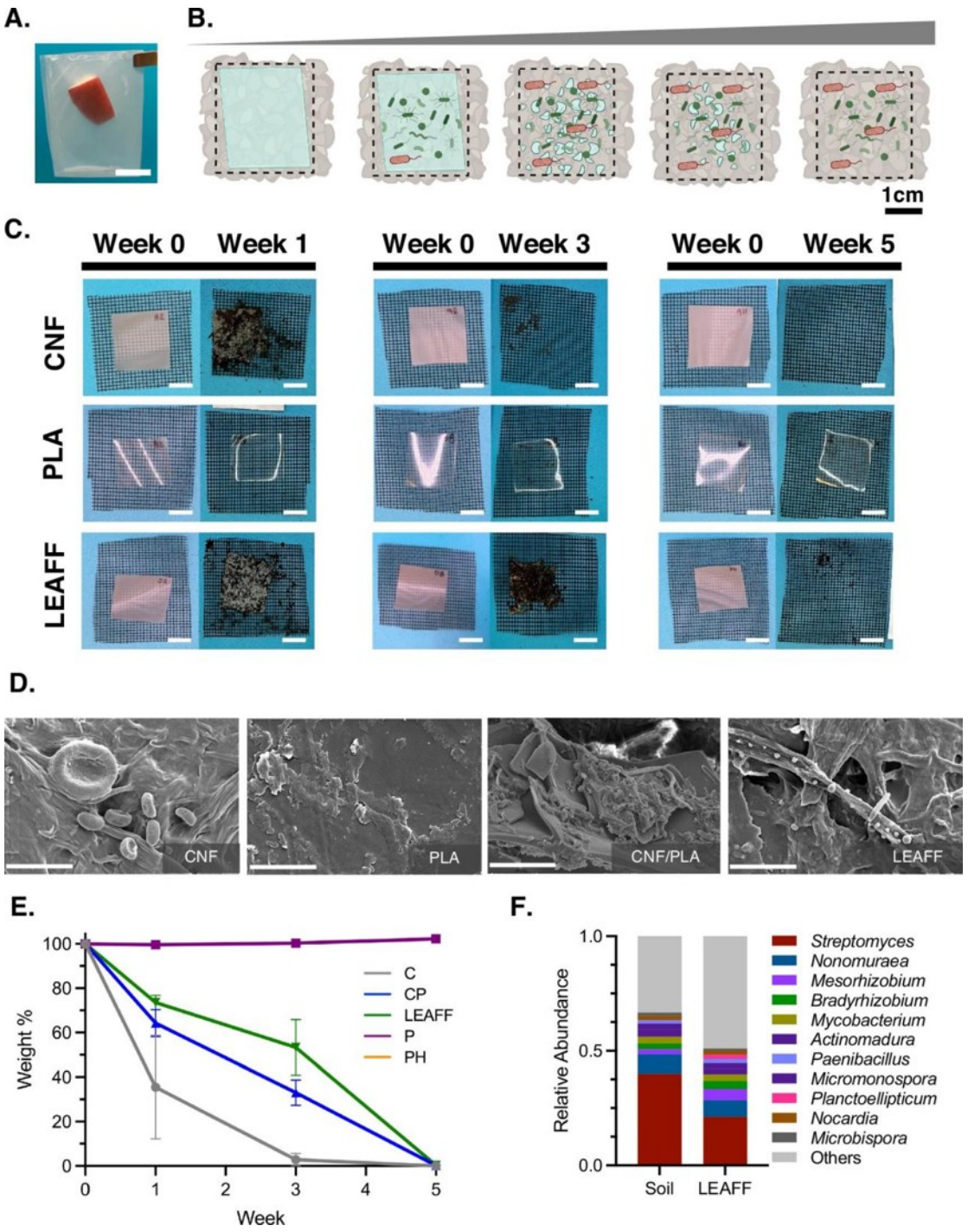

Fig. 12. Environmental biodegradation kinetics and microbial community profiling of the biomimetic layered, ecological, advanced, multi-functional film (LEAFF): (A) Appearance of LEAFF for food packaging applications; (B) Schematic illustration of the microbial biodegradation process; (C) Macroscopic photographic tracking of CNF, PLA, and LEAFF films during a 5-week soil degradation period; (D) Scanning electron microscopic images of the film surfaces after 2 weeks of degradation; (E) Gravimetric mass loss curves of the composite films; (F) Relative abundance of the microbial community at the genus level in the native soil *versus* the LEAFF degradation microenvironment. (Dhatt *et al.* (2025), CC BY-NC-ND 4.0).

Kegl *et al.* (2025) elucidated that the environmental benefits of biodegradable plastics are co-regulated by differences in degradation scenarios, accessibility of end-of-life disposal facilities, material modification strategies, and the risk of microplastic residues. In regions lacking industrial composting facilities or organic waste sorting systems, the life-cycle advantages of compostability-certified materials cannot be physically realized; conversely, if active packaging systems significantly reduce food waste by inhibiting spoilage, the positive environmental benefits at the system level will surpass the contributions generated by singular material substitution.

Real-environment degradation behavior and life cycle assessment constitute the dual physical foundation for the sustainability analysis of active packaging. The engineering evaluation of biodegradable active packaging relies on the following criteria: (1) the applicable environmental fate of the material (*e.g.*, industrial composting, home composting, soil degradation, or conventional solid waste) must be clearly defined, discarding generalized definitions of "biodegradability"; (2) degradation kinetic data spanning multiple environments and timescales must be provided, distinguishing degradation disparities between terrestrial and aquatic environments, and quantifying the perturbations of active components, cross-linking density, and fillers on the degradation rate; (3) a full life-cycle boundary encompassing raw material extraction, manufacturing energy consumption, end-of-life disposal, and food loss reduction benefits must be established. Only when materials maintain physicochemical stability during service, follow predictable degradation pathways in specific end-of-life scenarios, and demonstrate quantified net environmental benefits in life-cycle accounting, does the sustainable translation of biodegradable active packaging systems possess technical and ecological feasibility.

Industrialization challenges: From laboratory casting to industrial extrusion processing

The commercial translation of biodegradable active packaging relies on the successful transition of materials from laboratory-scale solution casting to continuous industrial manufacturing processes, including extrusion, film blowing, cast extrusion, co-extrusion, thermoforming, and lamination. Current academic research is predominantly based on solution casting due to its formulation flexibility and its suitability for incorporating natural extracts or heat-sensitive active compounds. However, large-scale industrial manufacturing primarily relies on melt extrusion and its derivative technologies. Solution casting operates *via* solvent evaporation and low-temperature drying, favoring the uniform dispersion of heat-sensitive active substances, but this approach is severely limited by long drying cycles, high energy consumption, and discontinuous production. Conversely, film blowing and cast extrusion depend on the forming of polymer melts under high-temperature and high-shear conditions, offering high throughput and compatibility with existing packaging infrastructure. This fundamental mechanistic divergence renders melt processing highly susceptible to inducing thermal degradation, volatilization of active agents, phase separation, melt viscoelastic instability, and narrowed processing windows (Westlake *et al.* 2023b; Weng *et al.* 2025; Sharma *et al.* 2025a; Kumar *et al.* 2025). Furthermore, blown film extrusion is primarily used for flexible films and bags, cast extrusion is suited for high-transparency films and subsequent thermoformable sheets, while co-extrusion and lamination serve as the dominant industrial pathways for optimizing mechanical and barrier properties (Sharma *et al.* 2025a; Weng *et al.* 2025; Kt and Panicker 2026).

For water- or solvent-based casting and continuous coating, drying is itself a critical scale-up step. Excessively rapid evaporation may cause surface skin formation, internal solvent retention, cracking, curling, pore formation, and nonuniform redistribution of active agents, whereas insufficient drying increases energy consumption and may lead to residual moisture, film blocking, and unstable storage properties. Continuous production further requires precise control of web speed, drying temperature, residence time, film thickness, roll tension, and active-agent distribution. These parameters must be balanced against the thermal sensitivity and volatility of natural extracts and essential oils to ensure both manufacturing stability and functional retention.

The suitability of these processing routes depends strongly on the molecular form and thermoplastic behavior of the biopolymer. Starch can be gelatinized and plasticized into thermoplastic starch, enabling extrusion and film formation, although moisture sensitivity, retrogradation, and a relatively narrow processing window often limit its independent use. Native cellulose generally undergoes thermal degradation before melting and is therefore more commonly employed as a reinforcing phase, coating, nanopaper, regenerated film, or chemically modified derivative rather than as a conventional melt-extruded matrix. Melt-processable biodegradable polyesters such as PLA, PBAT, PBS, and PCL can consequently serve as co-matrices, carrier layers, or structural layers that facilitate continuous extrusion, thermoforming, and multilayer production. In these hybrid systems, natural biopolymers contribute renewable content, reinforcement, barrier performance, and compatibility with active compounds, whereas the polyester phase primarily provides processability and dimensional stability. Therefore, blended, coated, and multilayer architectures currently offer a more practical route to commercial packaging than the direct replacement of conventional thermoplastics with unmodified starch or native cellulose.

The industrial processability of laboratory formulations is the prerequisite for scale-up production. Westlake *et al.* (2023b) noted that the incorporation of active agents frequently alters the mechanical, barrier, and rheological behaviors of bio-based films, leading to embrittlement, roll sticking, melt fracture, or interlayer instability during scale-up. Weng *et al.* (2025) categorized the material translation process into three tiers: laboratory methods (casting, dipping, spraying), pilot-scale acceptable techniques (brushing, roll coating, fluidized bed), and industrial manufacturing (extrusion blown film, calendering, injection molding). Formulations established in the laboratory must undergo rigorous rheological and thermodynamic evaluation to verify their feasibility under complex thermomechanical histories.

Recent studies have validated the continuous manufacturability of active packaging using industrial-grade blown film technologies. Kim *et al.* (2024) reported the development of an industrial-scale blown active box packaging film: An essential oil mixture of oregano and pyrethrum (O1T3) was first immobilized onto a celite carrier, followed by twin-screw extrusion blowing to prepare LLDPE/rice husk/active component composite films. Data demonstrated that the immobilized O1T3 carrier-maintained insect-repellent release activity for up to 14 days; among the evaluated systems, LLCBF-OTC0.5 exhibited the highest elongation at break and tensile strength, while maintaining color and opacity comparable to the control film. According to ISO 22196 standards, its antibacterial activity values against *E. coli* and *S. aureus* reached 4.9 and 3.5, respectively. Under simulated instant noodle box storage and transport conditions, its repellency against *Plodia interpunctella* and *Tribolium castaneum* increased by 8.12-fold and 2.17-fold, respectively. This result proves that volatile essential oils can be successfully integrated into continuous industrial blown film systems through carrier immobilization and masterbatch design.

In a pilot-scale acceptable study, Beltrán Sanahuja *et al.* (2025) developed PCL active films. The study utilized ultrasound-assisted extraction and fermentation technologies to enhance the thermal stability of antioxidants derived from pineapple by-products; post-fermentation, the succinic acid content increased from 12.0 ± 0.2 mg/100 g to 1120 ± 20 mg/100 g. The extracts were subsequently encapsulated in whey protein isolate (WPI), achieving encapsulation efficiencies of 87.4% and 89.1%, with the onset thermal degradation temperature of the encapsulated particles rising to 128±2 °C. During the scale-up processing, the active particles were extrusion-pelletized at 200 rpm and then processed *via* single-screw extrusion film blowing at 20–22 rpm. Physical testing indicated that the addition of the active extracts decreased the Young's modulus of the PCL film from 296 ± 8 MPa to 264 ± 13 MPa. However, in burger meat packaging tests, the film significantly inhibited TBARS proliferation, extending the freshness shelf life by over 10%. Furthermore, the study executed overall and specific migration tests in accordance with EU 10/2011, confirming the simultaneous requirement for processing feasibility, performance retention, and regulatory validation during scale-up.

The retention percentages and release controllability of active agents during melt scale-up directly impact product efficacy. Chen *et al.* (2025a) analyzed the sequence effect of adding cinnamon essential oil (CEO) during the processing of TPS/PBAT active films, comparing four melt sequences: simultaneous mixing of CEO with TPS/PBAT, pre-mixing CEO with starch, pre-mixing CEO with TPS, and pre-mixing CEO with PBAT. Characterization showed no significant differences in gas barrier properties among the four films; however, the P/T-C-2 (CEO pre-mixed with starch) system exhibited the strongest hydrogen bonding, optimal microscopic dispersion, highest absolute CEO retention, and maximal release in a 10% ethanol simulant, alongside demonstrating the most potent antibacterial effects against *E. coli*, *S. aureus*, and *S. putrefaciens*. Conversely, the mechanical properties of P/T-C-3 (CEO pre-mixed with TPS) severely deteriorated. The data indicate that in industrial melt processing, masterbatch design, addition sequence, and melting thermodynamic history govern the final phase morphology and functional evolution of active packaging.

The PBAT/TPS/grape seed extract (GSE) composite blown film prepared by Zhai *et al.* (2025) further verified the capacity of the extrusion process to carry active functions while revealing intra-system performance trade-offs. The films, prepared *via* melt blending and film blowing, showed that GSE primarily formed intermolecular hydrogen bonds with TPS, improving the oxygen barrier property of the film, albeit accompanied by a slight decline in mechanical performance. The PBAT/TPS/GSE film integrated UV blocking, antibacterial, and antioxidant functions; in accelerated shelf-life testing for peanut butter packaging, the predicted shelf life of the PBAT/TPS/GSE-5 film exceeded 300 days, approximately double that of conventional LDPE packaging. This study elucidates that industrial film blowing necessitates a re-optimization among active functionalization, barrier enhancement, and mechanical retention.

The diversification of industrial packaging terminal morphologies (*e.g.*, multilayer sheets, thermoformed trays, pouches, or box films) constitutes another layer of engineering challenges. Srisa *et al.* (2025) prepared PLA sheets containing 5 wt% EDTA, EMAL, or LAE *via* cast extrusion, and further processed them into active thermoformed trays. Gas permeation data indicated that the EMAL/LAE composite system reduced the oxygen transmission rate (OTR) by 68%. In bacon packaging tests, the EDTA/LAE combination exhibited a combined antimicrobial effect, reducing the target microbial concentration by >4 log within 7 days. Simultaneously, the incorporation of active additives lowered the

thermoforming temperature window of the sheets. This work advances active packaging validation from two-dimensional films to the level of three-dimensional commercial distribution components with complex structures.

For bakery foods, Promhuad *et al.* (2025) demonstrated the coupling mechanism between the film blowing process and headspace active gas release. Maltol (MT) and ethyl maltol (EM) were introduced into a TPS/PBAT (60:40) blend, approaching the limit for stable film blowing at a high TPS ratio. Results showed that films added with 1% to 5% EM/MT were successfully formed *via* extrusion, exhibiting contact antibacterial activity against *S. aureus*; the released volatile components effectively delayed fungal colonization on cream cake surfaces. The EMAL system achieved an inhibition zone of 1.53 mm against *Aspergillus niger*, extending the cake's shelf life by approximately 3-fold (up to a 13-day increase). These results establish the feasibility of volatile active agent headspace sustained-release systems in continuous industrial extrusion processing.

Synthesizing the aforementioned studies, the process scale-up from laboratory casting to industrial extrusion confronts five dimensions of engineering challenges: (1) Rheological and compatibility control: Cast systems are prone to phase separation, melt fracture, or bubble instability when subjected to the thermomechanical fields of melt extrusion; (2) Thermal stability and component retention: Natural extracts and volatile essential oils readily degrade or volatilize under high temperature and high shear, relying on microencapsulation, solid carrier adsorption, or masterbatch technologies to enhance retention; (3) Macroscopic structural forming: Materials must endure deformation stresses from secondary processing such as film blowing, co-extrusion, sheet calendaring, and thermoforming while preserving functionality; (4) Manufacturing homogeneity: Continuous industrial production demands strict batch-to-batch consistency in thickness distribution, active agent loading, roll thermomechanical stability, and release kinetics; (5) Cost constraints and regulatory compliance: Experimental formulations highly dependent on organic solvents, ultra-long curing cycles, expensive encapsulation costs, or those posing compliance risks lack industrialization potential.

The bottleneck in the engineering translation of biodegradable active packaging lies in converting laboratory-scale functional formulations into continuous manufactured products that are compatible with existing industrial processing equipment, possess stable processing windows, exhibit controllable active component retention, and comply with food contact material regulations. Technically viable commercial pathways require ensuring that the material systems achieve thermodynamic and rheological stable operation on industrial platforms such as twin-screw compounding, blown film extrusion, sheet extrusion, and thermoforming.

CONCLUSIONS AND FUTURE PERSPECTIVES

Biodegradable polymer composites constitute a critical material platform for active food packaging, concurrently addressing the reduction of packaging-derived environmental burdens and the extension of food shelf life *via* dynamic interfacial functions. The trajectory of this field has advanced beyond the direct substitution of petroleum-based plastics to the rational integration of matrix selection, interfacial engineering, active-agent incorporation, and structural design. This integration yields targeted combinations of antimicrobial, antioxidant, UV-shielding, gas-barrier, moisture-regulating, and stimuli-responsive functions. Across polysaccharide- (starch, cellulose,

chitosan, alginate/pectin) and protein-based systems, packaging performance is governed by the physicochemical coupling of polymer network architecture, additive dispersion state, interfacial compatibility, and active-agent release kinetics.

Biodegradable active packaging functions as an application-specific engineering system rather than a universal material formulation. Distinct food matrices impose heterogeneous preservation criteria. High-moisture animal products necessitate the synchronous mitigation of microbial proliferation, lipid oxidation, exudate accumulation, and sensory degradation. Conversely, respiring fruits and vegetables require the regulation of water transpiration, gas exchange fluxes, ethylene accumulation, and surface microbial activity, whereas bakery and low-moisture foods rely on volatile-release or headspace-active networks. Consequently, optimal packaging architectures are dictated by the specific deterioration pathways of the target food rather than isolated mechanical or barrier metrics of the film. The engineering viability of these materials depends on translating physicochemical designs into food-specific preservation strategies with quantifiable shelf-life extensions.

The industrial translation of these systems is subject to multi-dimensional constraints. First, enhancements in active functionality frequently induce trade-offs in rheological processability, optical clarity, mechanical stability, or biodegradation kinetics. Second, the safety evaluation of active matrices is governed by the migration of intentionally added substances (IAS), the generation of non-intentionally added substances (NIAS), and the condition-dependent migration of nanoparticles, encapsulants, or reactive carriers. Third, biodegradability constitutes an environment-dependent kinetic outcome dictated by disposal routes and microenvironmental conditions rather than a generalized material attribute. Fourth, the scalability of laboratory-scale solution-cast formulations depends on their thermomechanical compatibility with continuous melt-processing technologies, including twin-screw compounding, film blowing, cast extrusion, and thermoforming. Translating these systems requires maintaining functional efficacy, regulatory compliance, and manufacturability across formulation, processing, utilization, and end-of-life phases.

Despite the substantial progress achieved, the current evidence base remains uneven in several important respects. Differences in film conditioning, test protocols, storage conditions, and reporting metrics continue to limit quantitative comparison across material systems. The relationships among polymer-network structure, active-agent release, and food-specific preservation outcomes also remain largely empirical, with relatively few studies linking release profiles to defined spoilage thresholds under realistic and dynamically changing storage conditions. Long-term functional stability, active-agent depletion, sensory acceptance, and package-level performance under fluctuating temperature and humidity have received less attention than initial mechanical, barrier, or antimicrobial properties. In parallel, the migration and toxicological behavior of nanoparticles, released ions, and non-intentionally added substances require more comprehensive assessment, while biodegradation is still frequently inferred from short-term disintegration or mass loss rather than mineralization under realistic end-of-life conditions. Pilot-scale reproducibility, techno-economic feasibility, and direct benchmarking against functionally equivalent commercial packaging likewise remain insufficiently documented.

Addressing these gaps requires a transition from laboratory-scale functional films to packaging systems designed around industrial processing and commercial supply chains. Multi-objective material design should therefore simultaneously balance barrier

performance, active-agent release, mechanical integrity, migration compliance, processing stability, cost, and end-of-life behavior. AI-assisted material screening and process optimization may further support the development of scalable and sustainable packaging systems (Murugesan and Li 2026). Rigorous structure–property–function models are needed to correlate polymer-network topology, phase morphology, and carrier architecture with melt rheology, active-component retention, mass-transfer kinetics, and food-specific preservation outcomes. On the manufacturing side, solvent-free or water-based processing, low-energy drying, masterbatch formulation, thermally stable encapsulation, staged feeding, and multilayer architectures provide practical routes for transferring active components into twin-screw compounding, blown-film extrusion, cast-film extrusion, roll-to-roll coating, lamination, and thermoforming. Pilot-scale studies should define stable processing windows and establish quality-control criteria for film thickness, dispersion uniformity, active-agent loading, residual moisture or solvent, barrier performance, and release kinetics during continuous production. Commercial validation further requires comparison with functionally equivalent conventional packaging under realistic transportation and storage conditions, together with migration, sensory, shelf-life, and regulatory assessments. Raw-material variability, production throughput, encapsulation and processing costs, and compatibility with regional composting or recycling infrastructure should also be incorporated at the formulation stage. The commercial viability of natural biopolymer composites will ultimately depend on integrating polymer science, food preservation, processing engineering, toxicological assessment, techno-economic analysis, and end-of-life management within a unified packaging-development framework.

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Declaration of Competing Interest

The authors declare no competing interests

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