International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 13 Issue 3 ǁ March 2025 ǁ PP. 130-143

Progress of research and application of sodium alginate food packaging film

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Abstract
With the promotion of the global sustainable development strategy, the demand for eco-friendly materials in the food packaging sector has been continuously rising. Sodium alginate (SA), a natural anionic polysaccharide derived from brown algae, has gained significant attention as a novel food packaging material due to its excellent film-forming ability, biocompatibility, and biodegradability. However, pure SA films suffer from poor mechanical properties and limited moisture barrier performance, which restricts their practical applications in food packaging. Extensive research has demonstrated that the incorporation of other natural or synthetic polymers, nanomaterials, and functional active components can significantly enhance the properties of SA-based composite films. This review systematically summarizes recent advances in SA-based composite films, focusing on their major preparation methods, key functional characteristics, and applications in food packaging. Furthermore, the challenges associated with their practical applications and future research directions are discussed to provide insights for the development and application of SA-based food packaging materials.

Keywords: *Sodium alginate; Composite film; Food packaging*

Date of Submission: 14-03-2025 Date of acceptance: 30-03-2025

. Intruduction

With the rapid development of the food packaging industry and increasing consumer awareness of food safety and environmental protection, conventional plastic packaging materials are facing severe environmental challenges. Statistics indicate that the global annual production of plastics has exceeded 390 million tons, with a significant portion used for disposable packaging[1]. Traditional plastic packaging materials are primarily derived from non-renewable petrochemical resources and are highly resistant to degradation, persisting in the environment for centuries. This has led to severe microplastic pollution and long-term negative impacts on marine and terrestrial ecosystems[2]. Driven by the concept of sustainable development and the dual forces of social sustainability goals and consumer environmentalism, global attention toward eco-friendly food packaging materials has been increasing, leading to the continuous expansion of the sustainable packaging market. Among them, the development of biodegradable bio-based packaging materials has become a research hotspot. Sodium alginate (SA), a natural polysaccharide extracted from brown algae, has attracted significant interest in the food packaging sector due to its abundant availability, low cost, renewability, and excellent biodegradability[3].

SA is a linear, unbranched polymer composed of β-D-mannuronic acid (M) and α-L-guluronic acid (G) units, linked via 1,4-glycosidic bonds in three block arrangements: MM, GG, and MG. These structural units form cyclic configurations connected to a carboxyl (-COOH) group and two hydroxyl (-OH) groups in different orientations (Figure 1). SA exhibits excellent film-forming and gelation properties[4]. However, pure SA films have certain limitations, such as poor mechanical strength, low barrier properties, and inadequate antimicrobial and antioxidant functions, which hinder their practical application in food packaging[5]. To enhance the properties of SA films, researchers have employed composite modification strategies, including the incorporation of inorganic nanofillers, natural polymers, and bioactive components, as well as structural reinforcement through physical and chemical crosslinking. These modification approaches not only improve the mechanical and barrier properties of the films but also impart additional functionalities, such as antimicrobial and antioxidant activities, thereby enhancing food preservation performance.This review aims to systematically analyze and summarize recent research advances in SA-based composite films, including their preparation, property optimization, and applications in food packaging, while also providing insights into future research directions.

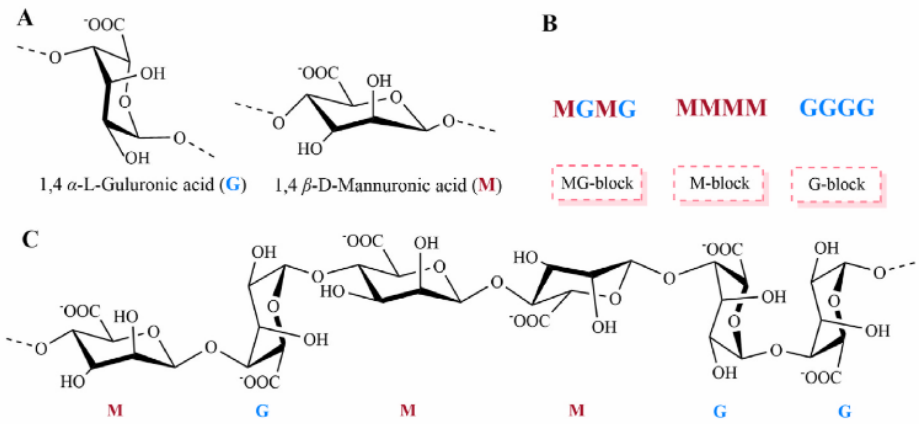

Fig.1 The structure of SA: monomers (a), blocks distribution (b), and chain conformation (c)[4]

. Preparation of Sodium Alginate Composite Films

2.1 Solution Casting Method

The solution casting method is one of the most commonly used techniques for preparing sodium alginate (SA)-based composite films. In this method, SA is dissolved in water or an appropriate solvent along with other polymers, plasticizers, or active components to form a homogeneous film-forming solution. This solution is then cast onto a mold or flat surface and left to dry under a well-ventilated environment or in an oven. As the solvent evaporates, solid materials gradually deposit, forming a film. Finally, the dried film is carefully peeled off from the casting surface and collected for further applications or analysis[6-7]. Due to its simplicity, low equipment requirements, and suitability for a wide range of composite materials, this method has been widely employed in food packaging, biomedical materials, and other fields.

In recent years, researchers have used the solution casting method to develop SA-based composite films and have improved their performance through various modification strategies[8]. Puscaselu et al.[9] incorporated steviol glycosides into the SA matrix to enhance the antioxidant activity and solubility of the film, preparing a functional SA composite film via the solution casting method. The study demonstrated that the addition of steviol glycosides not only increased the film's mechanical strength but also significantly improved its water solubility, making it suitable for edible packaging applications. Similarly, Saswat et al.[10] prepared calcium-ion-crosslinked biodegradable SA films via solution casting and investigated their potential in food packaging. Their findings showed that calcium ion crosslinking enhanced the film's tensile strength to 13.2 MPa while reducing its water vapor permeability, thereby improving its barrier properties. This result indicates that the combination of solution casting and crosslinking agents can effectively optimize film performance, making it more suitable for food preservation packaging.

Júnior et al.[11] successfully prepared hydrolyzed collagen (HC)-modified SA food packaging films using the solution casting method. The study revealed that HC incorporation significantly improved the film's film-forming ability and mechanical properties, with an optimal HC addition of 4% leading to an increase in tensile strength to 17.5 MPa and elongation at break (EB) to 18.6%. In another study, Singh et al.[12] developed sodium alginate/covalent organic framework (SA/COF) composite films via solution casting and explored their application in intelligent food packaging. The results indicated that COF incorporation not only enhanced the film's mechanical properties but also reduced its swelling ratio and water vapor permeability, thereby improving its water resistance and barrier performance. This study demonstrated that the combination of the solution casting method with functional nanofillers can endow SA films with multifunctional properties.

Due to its simplicity and broad applicability, the solution casting method remains the primary technique for fabricating SA-based composite films. By optimizing factors such as SA concentration, crosslinking agents, plasticizers, and functional fillers, the mechanical strength, barrier properties, and bioactivity of the films can be significantly improved. However, certain challenges persist, including uneven drying and difficulties in controlling the porous structure of the films. Future research may integrate strategies such as layer-by-layer self-assembly and crosslinking curing to further enhance the performance of films prepared via the solution casting method, thereby expanding their applications in food packaging.

2.2 Layer-by-Layer Assembly Method

The Layer-by-Layer (LbL) assembly method is an advanced technique for fabricating multilayer composite films. This approach is based on electrostatic interactions, hydrogen bonding, or covalent bonding, allowing for the alternate deposition of oppositely charged materials or those with specific interactions to

construct nanometer- or micrometer-scale layered structures. Initially developed for biomedical and nanomaterial applications, the LbL assembly method has recently been introduced into food packaging material fabrication to enhance mechanical properties, barrier performance, and bioactivity [13-14]. In the field of food packaging, SA, due to its negatively charged carboxyl groups, readily forms stable multilayer structures with positively charged biopolymers (e.g., chitosan, gelatin) or nanomaterials (e.g., zinc oxide nanoparticles) (Figure 2), thereby imparting superior mechanical properties, bioactivity, and functional characteristics to the films[15].

In recent years, significant progress has been made in the application of the LbL assembly technique for food packaging, particularly in active packaging, antimicrobial packaging, and intelligent responsive packaging. Kiattijiranon et al.[16] investigated the LbL assembly of SA and starch-based composite films and found that this method effectively enhanced water vapor barrier properties and mechanical strength. Additionally, the multilayer structure reduced permeability while increasing film flexibility, making it more suitable for food packaging applications. Similarly, Shan et al.[17] fabricated SA/gelatin-polyphenol multilayer composite films via LbL assembly, using green tea extract as a crosslinking agent to enhance antioxidant and antibacterial properties. Their results showed significant inhibition of Escherichia coli and Staphylococcus aureus, demonstrating the film's potential for active food packaging applications. Wang et al.[18] developed chitosan, SA, and carboxymethyl chitosan-ZnO nanoparticle composite films via LbL assembly. The results indicated a significant improvement in tensile strength, while the addition of ZnO nanoparticles enhanced antibacterial activity and photostability, making the films highly promising for food preservation and intelligent packaging. In another study, Yutong et al.[19] prepared polylactic acid/poly(butylene adipate-co-terephthalate) (PLA/PBAT)/SA multilayer active packaging films using the LbL assembly method. The incorporation of multilayer structures effectively improved mechanical strength and barrier properties, with the SA layer enhancing flexibility and the PLA/PBAT layer providing superior mechanical strength and water vapor barrier performance.

Furthermore, Shah et al.[20] developed chitosan/SA/ethyl cellulose multilayer composite films and incorporated L-ascorbic acid to improve barrier performance and antioxidant capacity. Their findings showed that unmodified SA films exhibited relatively low tensile strength (TS), whereas crosslinked composite films demonstrated an increase in TS to 29.7 MPa and an elongation at break (EB) of 15.4%. The synergistic crosslinking effect of ethyl cellulose and chitosan not only enhanced tensile strength but also optimized film flexibility. This study highlights the significant potential of the LbL assembly method in developing high-performance food packaging materials.

Despite its advantages, the LbL assembly method still faces certain challenges, such as process complexity and industrial scalability limitations. Future research could focus on optimizing film formation processes, such as incorporating nanoparticle reinforcements and designing multifunctional layered structures, to further enhance the overall performance of LbL-assembled films and facilitate their applications in food packaging and related fields.

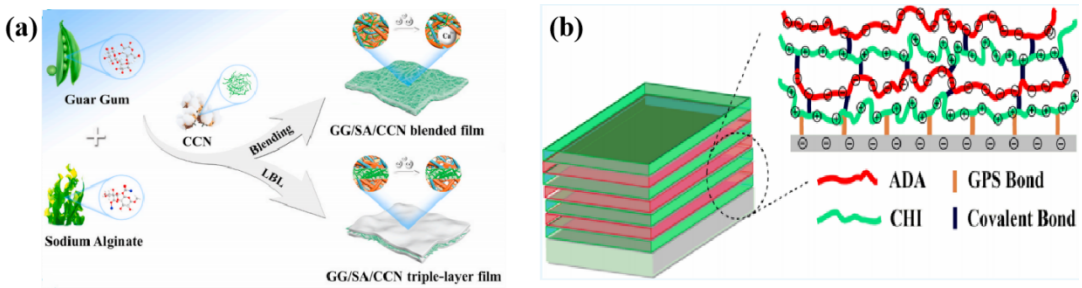

Fig. 2 (a) Schematic diagram of guar gum/carboxycellulose nanofibers//sodium alginate composite membrane prepared by layer-by-layer self-assembly method[15];
(b) Schematic diagram of chitosan/alginate dialdehyde multilayer membrane prepared by layer-by-layer self-assembly method[13]

2.3 Electrospinning Method

Electrospinning technology provides an efficient and controllable nanoscale processing method for the fabrication of SA-based composite films. This technique utilizes a high-voltage electric field to stretch polymer solutions or melts into nanofibers, which can be produced in various forms, as shown in Figure 3, including emulsion electrospinning, blend electrospinning, and coaxial electrospinning[21]. Due to its advantages, such as ease of operation, controllable fiber diameter, and wide material compatibility, electrospinning has been widely applied in food packaging, biomedicine, and functional materials[22]. In the fabrication of SA composite films, electrospinning enhances the specific surface area and improves the pore structure, thereby optimizing mechanical properties, antibacterial activity, and suitability for food packaging applications[23].

In recent years, researchers have explored the electrospinning performance of SA in combination with

polymers such as polyvinyl alcohol (PVA), chitosan (CS), and polyethylene glycol (PEG), optimizing electrospinning parameters to enhance the mechanical strength, moisture barrier properties, and bioactivity of the films. Dede et al.[24] used electrospinning to load Satureja hortensis essential oil onto SA-based fibrous films and evaluated their antimicrobial efficacy against foodborne microbial contamination. Their results demonstrated that the composite films effectively inhibited both Gram-positive and Gram-negative bacteria while maintaining good transparency and mechanical strength, offering a novel approach for edible food packaging. Castellano et al.[25] investigated the synergistic effects of silver nanoparticles (AgNPs) incorporated into electrospun SA-based films. Their study showed that these films exhibited an inhibition rate exceeding 90% against Staphylococcus aureus and Escherichia coli, with the antibacterial effect primarily attributed to the oxidative stress response of AgNPs, which caused bacterial membrane rupture.

Surendhiran et al.[26] developed SA/polyethylene oxide (PEO) nanofiber films loaded with brown algae polyphenols using electrospinning for chicken meat preservation. The results indicated that these films effectively inhibited Salmonella growth, reduced oxidative stress, and extended the shelf life of chicken meat. The antioxidant activity was primarily attributed to the free radical scavenging ability of brown algae polyphenols, which effectively delayed food quality deterioration. Amjadi et al.[27] fabricated zein/SA nanofiber composite films via electrospinning and further enhanced their properties by incorporating titanium dioxide nanoparticles (TiO NPs) and betaine. Structural and physical analysis revealed that the films exhibited high tensile strength and elongation at break (12.61 MPa / 40.40%). TiO NPs formed a physical filling network within the nanofiber structure, reinforcing hydrogen bonding between fibers, while the addition of betaine endowed the films with enhanced functional activity.Aloma et al.[28] investigated the electrospinning behavior of SA/PVA blend solutions and examined the effect of PVA content on fiber formation. Their findings showed that increasing the PVA content improved the viscosity and conductivity of the spinning solution, resulting in more uniform fiber structures. Additionally, the composite films exhibited significantly enhanced mechanical properties and reduced water solubility compared to pure SA films, offering new possibilities for food packaging applications.With the development of novel nanomaterials and intelligent food packaging technologies, electrospun SA-based composite films hold great potential as the next generation of biodegradable, high-performance food packaging materials, contributing to both food safety and environmental sustainability.

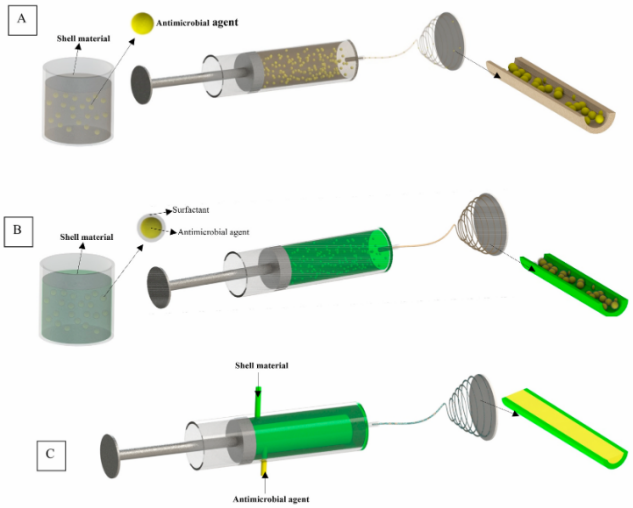

Fig.3 Various methods to produce nanofibers through electro spinning (A) emulsion electrospinning; (B) blend electrospinning; (C) coaxial electrospinning[21]

. Optimization of properties of sodium alginate composite films

3.1 Mechanical Properties

The mechanical performance of sodium alginate (SA) composite films is primarily optimized through three strategies: crosslinking modification, nanomaterial reinforcement, and multi-component blending. These approaches exhibit varying effects on enhancing tensile strength (TS) and elongation at break (EB), influencing the film's rigidity and flexibility by regulating its internal microstructure.

3.1.1 Crosslinking Modification

Crosslinking modification is a widely adopted strategy to improve the TS of SA-based films, categorized into physical crosslinking and chemical crosslinking. Physical crosslinking via Ca^{2} ionic bonding has been extensively studied. Giz et al.[29] investigated the effects of different calcium ion concentrations and glycerol plasticization on the mechanical properties of SA films. They found that with 20% glycerol addition

and 1.5% Ca^{2} crosslinking, the TS increased to 189.8 MPa, while the EB was 6.6%. This study highlighted that Ca^{2} crosslinking effectively strengthens the film, whereas glycerol plasticization partially compensates for flexibility loss. Chemical crosslinking involves the formation of stronger covalent or hydrogen bonds. Ruan et al.[30] crosslinked SA films using truxillic acid (CBDA), a natural polyphenol with strong hydrogen bonding capacity and potential esterification reactivity. Their results showed that CBDA crosslinked films exhibited a TS of 148 MPa, marking a 39.6% increase compared to pure SA films, while also enhancing antibacterial and biodegradation properties. Metal-polyphenol networks (MPNs) have also been explored for reinforcing SA-based films. He et al.[31] demonstrated that Fe^{3} -polyphenol complexation significantly enhanced intermolecular interactions within SA films. Their study reported that the TS of unmodified SA films was only 15.6 MPa, with an EB of 8.2%, whereas after MPNs crosslinking, the TS increased to 32.5 MPa, while EB remained relatively stable at 7.9%. The increased Young's modulus indicated improved stiffness, while maintaining some flexibility, making the films more resistant to mechanical stress.

3.1.2 Nanomaterial Reinforcement

Nanofiller incorporation, particularly nanocellulose, has been effective in enhancing hydrogen bond networks, thereby increasing TS, although the effect on EB varies. Zhang et al.[32] developed cellulose nanofiber (CNF)/SA composite films with high strength, water resistance, and transparency. Their findings indicated that at 50% CNF content, the dry-state TS reached 125 MPa, while wet-state TS was 33 MPa. In dry conditions, CNF formed a tightly interwoven network with SA, resulting in a linear increase in TS and Young's modulus. However, under wet conditions, the hydrophilic nature of CNF led to water bridge formation, disrupting fiber interactions and causing a decline in wet strength.

3.1.3 Multi-Component Blending

Multi-component blending combines the advantages of different materials to optimize both TS and EB. Liu et al.[33] examined the effects of catechin and tannic acid on SA/gelatin/polyvinyl alcohol (PVA) composite films. Their study found that the unmodified film had a TS of 8.12 MPa and an EB of 42.82%. Upon tannic acid incorporation, TS increased to 15.49 MPa, while EB significantly improved to 133.16%. Compared to catechin, tannic acid's multiple binding sites facilitated uniform crosslinking, strengthening hydrogen bonding while retaining flexibility, making it more suitable for food preservation applications.

Crosslinking modification primarily enhances intermolecular interactions, significantly increasing TS, but may reduce EB unless plasticizers are incorporated. Nanofiller reinforcement (e.g., nanocellulose) greatly improves TS, but can lead to a loss of flexibility due to increased rigidity. Multi-component blending effectively balances TS and EB, while introducing additional functionalities (e.g., antioxidant activity), making it ideal for food packaging applications. Each strategy should be selected based on specific application needs to achieve optimal comprehensive performance in SA-based composite films.

3.2 Barrier Properties

The barrier properties of sodium alginate (SA) films are primarily influenced by their molecular structure, crosslinking methods, composite materials, and plasticizers. In recent years, researchers have optimized the water vapor permeability (WVP) and oxygen transmission rate (OTR) of SA composite films using multi-component blending, ionic crosslinking, and nanomaterial incorporation. Each method demonstrates distinct effects on gas and moisture barrier performance.

3.2.1 Ionic Crosslinking Modification

Ionic crosslinking enhances the degree of crosslinking by forming ionic bonds, which reduces the exposure of hydrophilic groups and thereby decreases water vapor permeability. Choi et al.[34] investigated the effects of Ca^{2} , Ba^{2} , and Zn^{2} crosslinking on the water resistance of SA films. Their results showed that Ba^{2} -crosslinked films exhibited the best water resistance, with a swelling ratio of only 45.8%, significantly lower than that of Ca^{2} -crosslinked films (68.2%). Additionally, Ba^{2} crosslinking reduced WVP by 42%, indicating improved barrier properties under high-humidity conditions. In contrast, Zn^{2} -crosslinked films demonstrated superior mechanical strength and swelling resistance, making them more suitable for liquid food packaging applications.

3.2.2 Multi-Component Blending

Multi-component blending enhances hydrogen bonding networks and intermolecular interactions, leading to a denser film structure and improved barrier properties. Ramakrishnan et al.[35] examined the gas and moisture barrier performance of SA/carboxymethyl cellulose (CMC)/starch composite films. Their study found that CMC and starch reinforced film compactness through hydrogen bonding, significantly improving barrier properties. The WVP of SA/CMC films was 3.42 × 10 g·mm ^{2}·d ^{1}·Pa ^{1}, and the OTR was 6.52 × 10

m ²·d ¹·kPa ¹. When the CMC-to-starch ratio was 1:1, WVP further decreased by 31% to 2.36 × 10 g·mm ²·d ¹·Pa ¹, while OTR dropped by approximately 65% to 2.26 × 10 m ²·d ¹·kPa ¹, significantly enhancing food storage stability. Marangoni et al.[36] studied the effects of silicon dioxide (SiO) nanoparticles on the barrier properties of SA/citrus pectin composite films. Adding 5% and 7.5% SiO significantly reduced WVP, from 319.8 ± 38.7 g·m ²·day ¹ to 288.9 ± 23.5 g·m ²·day ¹ and 276.5 ± 6.5 g·m ²·day ¹, respectively. The strong hydrogen bonding interactions between SiO and the biopolymer matrix contributed to film densification, effectively hindering moisture diffusion. Li et al.[37] investigated the effects of black wolfberry anthocyanins (BWA) and CaCl crosslinking on the water barrier properties of SA composite films. Their study showed that Ca² -induced ionic crosslinking enhanced the polymer network, reducing water penetration channels, while the hydrophobic interactions of BWA's polyphenol structure further improved moisture resistance. Specifically, the WVP of uncrosslinked SA-BWA films was 6.1 × 10 ¹² g·cm ²·s ¹·Pa ¹, but after 5% CaCl treatment, it dropped by 73% to 1.6 × 10 ¹² g·cm ²·s ¹·Pa ¹.

3.2.3 Nanomaterial Reinforcement

Nanofiller incorporation effectively modifies the film's microporous structure, enhancing compactness and barrier properties. Wu et al.[38] explored the impact of nano-mica platelets on the barrier properties of SA composite films. Their findings revealed that the OTR of SA/nano-mica films was approximately 18.52 cc·m ²·day ¹·bar ¹. The oriented and orderly distribution of nano-mica layers within the film matrix increased the complexity of the moisture diffusion pathway, significantly improving water vapor barrier performance.

Multi-component blending significantly enhances WVP and OTR by strengthening the hydrogen bond network, making it suitable for food packaging applications. Metal ion crosslinking, especially Ba² crosslinking, effectively reduces water sensitivity, allowing films to maintain superior barrier properties in high-humidity environments. Nanomaterial incorporation improves film structure compactness, reducing WVP and enhancing gas barrier performance. Different SA composite films can be tailored based on specific food packaging requirements to achieve the desired barrier properties.

3.3 Thermal Stability

In recent years, researchers have significantly enhanced the thermal stability of sodium alginate (SA) composite films through nano-composite modification, oil-phase filling, and functional additives. These methods show distinct effects on improving the onset decomposition temperature ($T_{o\ e}$), maximum decomposition temperature (T_{ax}), and carbon residue rate (CR).

3.3.1 Oil-Phase Filling

Oil-phase filling can reduce the thermal oxidation rate through hydrogen bonding between fatty acids and SA molecules, providing a hydrophobic protective layer that decreases moisture and oxygen diffusion rates. This process delays thermal degradation and increases the thermal decomposition temperature of SA films. Kowalonek et al.[39] investigated the effects of raspberry seed oil (RSO) and black currant seed oil (BCSO) on the thermal stability of SA composite films using thermogravimetric analysis (TG-DTG). Their results revealed five distinct decomposition stages at 125°C, 125–300°C, 310–410°C, 410–510°C, and 750–1000°C, corresponding to the degradation of oil and surfactants. The carbon residue (CR) of SA films containing 25% RSO was 5.8%, while films with 25% BCSO had a CR of 6.5%, indicating that both oils contributed to improved thermal stability.

3.3.2 Nanomaterial Reinforcement

Nanomaterial incorporation improves the thermal stability and heat resistance of SA composite films by forming nano-barriers and reinforcing molecular networks. Li et al.[40] developed a fish scale gelatin/SA/thymol-loaded ZIF-8 nanoparticle composite film and systematically studied its thermal properties. Their results showed that the $T_{o\ e}$ of the composite film was 71.03°C, T_{ax} was 307.03°C, and CR reached 25.06%. The ZIF-8 nanoparticles formed an internal nano-barrier, limiting thermal oxidative degradation and reducing mass loss, thereby enhancing thermal resistance. Liu et al.[41] studied the effects of graphene oxide (GO) and amine-functionalized graphene oxide (AGO) on the thermal stability of SA composite films using thermogravimetric analysis (TGA). Their results showed that the $T_{o\ e}$ of the composite films ranged from 200 to 270°C, significantly higher than that of pure SA films. The improvement was attributed to GO forming hydrogen bonds with SA, while AGO provided both hydrogen bonding and electrostatic interactions via its protonated amine groups, significantly enhancing heat resistance and structural stability. Yu et al.[42] developed an active packaging film based on polyvinyl alcohol (PVA)/anthocyanins/SA, incorporating soybean hull nanocellulose (SHNC) to enhance thermal stability. Their study found that the T_{ax} of the composite film increased to 250–300°C, while CR decreased with increasing SHNC content. The large specific surface area of SHNC provided additional

crosslinking sites (e.g., hydrogen bonds and ester bonds), promoting a more compact three-dimensional network, thereby significantly improving thermal stability and making the film more suitable for food packaging applications.

3.3.3 Functional Additives

Functional additives capture free radicals (·OH, O) generated by thermal oxidation, thereby suppressing high-temperature oxidation, reducing thermal oxidative loss, and increasing CR, effectively improving the heat resistance of SA films. Hoque et al.[43] developed an active packaging film composed of pectin and SA, incorporating microcrystalline cellulose (MCC) and geraniol (GER) to enhance thermal stability. Using differential scanning calorimetry (DSC) and TGA, they found that the $T_{o\ e}$ of the pectin/SA film was 194.9°C, T_{ax} was 236.76°C, and CR was 26.42%. However, after adding MCC and GER, the $T_{o\ e}$ increased to 220.84°C, T_{ax} to 260.10°C, and CR to 32.44%, demonstrating a synergistic enhancement of SA film thermal stability.

Oil-phase filling reduces thermal oxidation rates via hydrogen bonding, increasing the thermal decomposition temperature by 17–22°C, making SA films suitable for high-temperature food packaging. Nanomaterial reinforcement primarily enhances thermal stability through nano-barrier effects or rigid network reinforcement. Different modification strategies can be selected based on specific application needs, optimizing thermal stability and expanding the use of SA composite films in high-temperature packaging applications.

3.4 Antioxidant Properties

Recent research on the antioxidant properties of sodium alginate (SA) composite films has focused on phenolic compound doping and natural antioxidant loading. These modification strategies effectively enhance the free radical scavenging ability of SA composite films, improving their capacity to inhibit food oxidation and spoilage, thus demonstrating great potential for applications in active food packaging.

3.4.1 Phenolic Compound Incorporation

Phenolic compounds (e.g., tannic acid (TA), catechol) significantly enhance the antioxidant capacity of SA composite films by donating hydrogen atoms, scavenging free radicals, and forming hydrogen bonds to stabilize the film structure. Li et al.[44] investigated the antioxidant effects of tannic acid (TA) in SA composite films. TA significantly enhanced the free radical scavenging ability of SA films while forming hydrogen bonds with SA molecules, improving film stability. Their results showed that the DPPH free radical scavenging rate of the SA-TA composite film reached 89.2%, indicating strong antioxidant capacity and improved food storage stability. Zhang et al.[45] explored the synergistic effect of tannic acid (TA) and silk fibroin (SF) modification on the antioxidant performance of SA films for fresh-cut apple packaging. The DPPH radical scavenging rate of the SA-SF composite film was below 20%, but with the addition of 0.3% TA, this value increased to 75.15%. The synergistic effect between SF and TA significantly enhanced the antioxidant activity of the SA composite film, prolonging the storage time of fresh-cut apples and improving their preservation quality. Chen et al.[46] studied the effect of different concentrations of thymol on the antioxidant performance of SA composite films. Their findings showed that the DPPH radical scavenging rate of SA-thymol composite films increased significantly with thymol concentration, reaching a maximum of 82.11% at 10 mg/mL thymol, confirming that phenolic acid compounds exhibit excellent antioxidant activity and effectively delay food oxidation and spoilage.

3.4.2 Natural Antioxidant Loading

Natural antioxidants (e.g., citrus byproducts) introduce bioactive sites that enhance free radical scavenging activity and prolong food shelf life when used in food packaging. Yun and Liu[47] developed SA-based active food packaging films with twelve different mandarin peel powders (MPP) and evaluated their free radical scavenging ability and food preservation effects. The study found that the total phenolic content (TPC) released in 95% ethanol ranged from 2.06 to 2.86 mg GAE/g, while the DPPH radical scavenging activity ranged from 13.94 to 22.91 μmol TE/g. A strong positive correlation ($R^2 = 0.94$) was observed between the antioxidant release capacity and the total phenolic content of MPP, indicating that higher polyphenol content contributed to stronger antioxidant activity. Eltabakh et al.[48] functionalized SA/maltodextrin (SA/MD) composite films with Azolla pinnata leaf extract (APLE) to enhance their antioxidant capacity. The unmodified SA/MD film exhibited a DPPH radical scavenging rate of 30.2%, whereas adding 1.6% APLE increased the DPPH scavenging rate to 84.15% and the ABTS scavenging rate to 69.45%. This significant antioxidant enhancement was attributed to the high polyphenol and flavonoid content in APLE, which efficiently scavenged free radicals and slowed down food oxidation.

Both phenolic compounds and natural antioxidants effectively enhance the antioxidant properties of SA composite films. Optimization through different modification strategies can maximize the antioxidant performance of SA films to meet the requirements of food packaging applications, ultimately extending food

shelf life.

3.5 Antibacterial Properties

The antibacterial properties of sodium alginate (SA) composite films have been extensively studied for applications in food packaging. Studies show that the incorporation of antibacterial agents such as silver nanoparticles (AgNPs), zinc oxide nanoparticles (ZnONPs), and titanium dioxide nanoparticles (TiO NPs) can effectively inhibit bacterial and fungal growth, thereby extending food shelf life.

3.5.1 Silver Nanoparticles (AgNPs)

Silver nanoparticles (AgNPs) are broad-spectrum antibacterial agents that can bind to bacterial cell walls, disrupt metabolic functions, and induce cell death, thereby enhancing the antibacterial properties of SA composite films.Zhang et al.[49] developed a self-supporting choline alginate–tannic acid–silver nanoparticle composite film for strawberry preservation. The study found that this composite film effectively inhibited Escherichia coli (E. coli) and Staphylococcus aureus (S. aureus) while significantly delaying mold growth on strawberries. This antibacterial effect was mainly attributed to AgNPs disrupting bacterial cell membranes and inhibiting metabolism, leading to long-term antibacterial performance. Srichaiyapol et al.[50] investigated the role of tannic acid (TA)–AgNP-modified SA composite films in biofilm inhibition. Their results showed that this material effectively destroyed the biofilms of methicillin-resistant Staphylococcus aureus (MRSA) and Pseudomonas aeruginosa, providing a novel antibacterial strategy for food packaging.

3.5.2 Zinc Oxide Nanoparticles (ZnONPs)

ZnONPs exhibit dual antibacterial mechanisms: (1) direct release of Zn^{2} ions, which disrupt bacterial cell walls, and (2) generation of reactive oxygen species (ROS) under light irradiation, further enhancing the antibacterial performance of SA composite films. Song et al.[51] studied Zn^{2} -crosslinked SA–bacterial cellulose–ZnO composite films and tested their antibacterial properties. The results showed that this composite film exhibited excellent antibacterial effects against E. coli (96.4% inhibition) and S. aureus (98.7% inhibition). Additionally, the incorporation of ZnO nanoparticles improved both the antibacterial performance and mechanical strength of the films, making them more suitable for food packaging applications. Zhang et al.[52] fabricated a sodium alginate–κ-carrageenan–gelatin multilayer composite film incorporating ZnO nanoparticles (ZnO NPs) and oregano essential oil (OEO) to enhance antibacterial performance. The study demonstrated that this multilayer structure significantly improved both the mechanical properties and antibacterial activity of the films. The synergistic effect of ZnO NPs and OEO effectively inhibited the growth of E. coli and S. aureus, while also enhancing the antioxidant properties of the film.

3.5.3 Titanium Dioxide Nanoparticles (TiO NPs)

TiO NPs are widely used for antibacterial modification of SA composite films due to their long-lasting antibacterial activity and antioxidant properties. Tang et al.[53] investigated the antibacterial modification of SA films with Au-TiO nanocomposites, developing a biodegradable SA/Au-TiO composite film with photocatalytic antibacterial properties for active food packaging applications. The study revealed that when Au-TiO nanoparticle content reached 2%, the composite film exhibited antibacterial rates of 87.1% against E. coli and 90% against S. aureus. This significant antibacterial effect was primarily attributed to the photocatalytic properties of TiO , which generated reactive oxygen species (ROS) under UV irradiation, leading to bacterial membrane damage. Furthermore, electron spin resonance (ESR) experiments showed that Au nanoparticles enhanced the visible-light response of TiO , producing hydroxyl radicals ($OH\cdot$) and superoxide radicals ($O \cdot$), allowing the film to retain good antibacterial activity even under low-light conditions.

The incorporation of AgNPs, TiO NPs, and ZnONPs significantly enhances the antibacterial properties of SA composite films:AgNPs primarily act by disrupting bacterial cell walls. ZnO NPs function through Zn^{2} ion release and photocatalytic ROS production. TiO NPs exhibit long-lasting antibacterial effects through photocatalysis and ROS generation. Different antibacterial strategies can be selected and optimized based on specific application requirements to maximize the antibacterial performance of SA composite films and improve food preservation. Future research should focus on intelligent antibacterial strategies and natural antibacterial agents to develop high-performance, sustainable SA-based antibacterial films for food packaging applications.

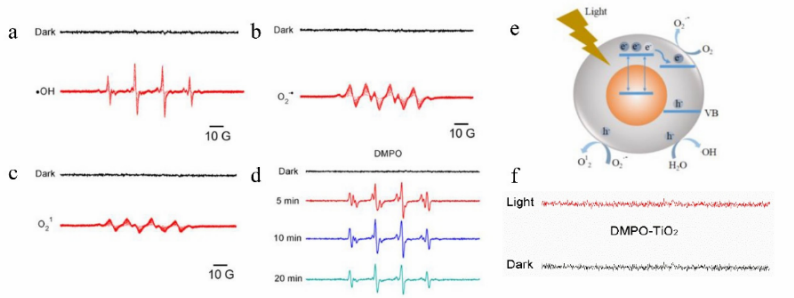

Fig. 3 Antibacterial activity and photocatalytic antibacterial mechanism of SA/Au-TiO_2 nanocomposite films[53]

. Applications of Sodium Alginate Composite Films in Food Packaging

4.1 Freshness Preservation of Fruits and Vegetables

Sodium alginate (SA) has gained widespread attention in food packaging due to its excellent film-forming ability, biocompatibility, and biodegradability. In recent years, researchers have developed high-performance composite films through antioxidant modification, antibacterial enhancement, and pathogen control strategies to improve the storage and preservation of fruits and vegetables. These modification mechanisms—such as electrostatic crosslinking, delivery system construction, and synergistic slow release—provide a scientific basis for optimizing the functionality of food packaging films.

4.1.1 Enhancing Physical Barrier and Antioxidant Properties

To address issues such as moisture loss, firmness reduction, and enzymatic browning in stored fruits and vegetables, researchers have employed functional modification techniques to strengthen the physical barrier and antioxidant capacity of SA-based films. These modifications slow metabolic rates and enhance storage stability.Yang et al.[54] developed an SA composite film incorporating yeast and sucrose, which was applied to longan fruit preservation. The study demonstrated that the composite film significantly reduced the activity of polyphenol oxidase (PPO) and peroxidase (POD), lowering their levels to 400±35 U/g and 1075±24 U/g after 8 days of storage. This represented a 31% and 56% reduction, respectively, compared to the control group (582±25 U/g and 475±19 U/g). The browning index decreased by 50%, and weight loss was reduced by 54%, confirming that the SA/CMC-SWE composite film effectively inhibited PPO and POD-mediated browning reactions and prevented moisture loss, thereby extending the storage life of fruits. Thivya et al.[55] developed an SA–carboxymethyl cellulose (CMC) composite packaging film incorporating red onion peel extract (SWE) to enhance its antioxidant and anti-browning properties. The study found that the polyphenols and antioxidants in SWE inhibited the PPO activity in apples, effectively preventing enzymatic browning. Additionally, the composite film demonstrated excellent moisture barrier properties, reducing the weight loss of fresh-cut apples and potatoes (by 2.79% and 6.02%, respectively). The hardness retention of apples and potatoes was also superior to the control group, decreasing from 1.89 N to 0.34 N for apples and from 4.31 N to 2.98 N for potatoes, demonstrating the effectiveness of SA composite films in preserving textural quality. El-Basiouny et al.[56] studied the preservation effects of Aspergillus flavus-mediated chitosan (CS)/AgNPs and CS/SeNPs composite films on tomatoes. After 14 days of storage, these composite films significantly improved tomato firmness by 13% and 33%, respectively. Furthermore, they reduced weight loss to 1.18±0.27% and 0.87±0.219%, compared to 3.07±0.192% in the control group, representing an improvement of 62% and 72%.

4.1.2 Pathogen Control for Shelf-Life Extension

To control pathogens in fruit and vegetable storage, researchers have explored natural antibacterial agents, nano-antibacterial materials, and crosslinking modifications to enhance the antibacterial properties of SA composite films, effectively preventing spoilage and extending shelf life. Ruchika et al.[57] prepared a chitosan–sodium alginate composite film (CS-SA-PTB) incorporating pterostilbene nanoemulsion (PTBNE) for mushroom preservation. As shown in Figure 4a, the composite film exhibited a high antibacterial rate, inhibiting E. coli (83.18±2.5%), S. aureus (90.69±3.7%), Gordonia terrae (99.06±0.44%), and Bacillus subtilis (99.24±0.5%). After 10 days of storage, the mushroom weight retention rate was 38.95±4.8%, with a size retention of 43.56±9.3%, compared to only 2.27±1.16% in the control group, indicating a 19-fold improvement in preservation effectiveness and a significant reduction in spoilage incidence. Chen et al.[58] constructed an active packaging film by electrostatically crosslinking camellia seed protein (CSP) with SA, applying it to strawberry preservation (Figure 4b). The film demonstrated 90% antibacterial efficacy against E. coli and S. aureus. After 7 days of storage, the weight loss rate of strawberries was reduced to 32%, a 65% improvement compared to the control group (85%), effectively extending the shelf life of strawberries. Farousha et al.[59]

developed an SA–starch composite film loaded with mesoporous silica (MCM-41) encapsulating date seed extract (DSE) to enhance antioxidant and antibacterial properties in food packaging. The high concentration of DSE@MCM-41 composite films exhibited strong antibacterial effects against E. coli and S. aureus due to the release of phenolic compounds and polyphenolic aromatic structures, which disrupted bacterial membrane integrity and increased permeability, ultimately leading to bacterial cell death. The slow release of bioactive components in DSE significantly enhanced the antioxidant and antibacterial properties of SA-based composite films, demonstrating their potential for food packaging applications.

These studies highlight that synergistic enhancement mechanisms achieved through molecular interactions such as electrostatic crosslinking and nanocomposites are key to improving the freshness preservation performance of SA composite films. Precise component formulations not only enhance the physical barrier properties of the films but also provide multiple preservation mechanisms through enzyme activity regulation, pathogen inhibition, and free radical scavenging. Tailored active preservation systems can be developed to meet the specific needs of different fruits and vegetables. These findings provide a scientific foundation and technological pathway for the development of next-generation intelligent food packaging materials.

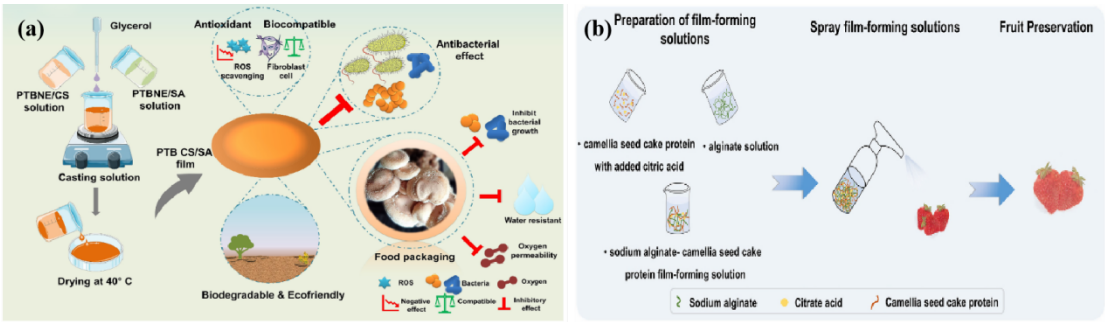

Fig.4 a Schematic diagram of chitosan/sodium alginate composite film doped with pterostilbene nanoemulsion (PTBNE) for mushroom preservation[57] b Schematic diagram of camellia seed protein (CSP) and sodium alginate composite film for strawberry preservation[58]

4.2 Preservation of Meat and Aquatic Products

Sodium alginate (SA), owing to its tunable film-forming properties and biocompatibility, exhibits significant advantages in the preservation of meat and aquatic products. In recent years, researchers have developed multifunctional composite films by incorporating intelligent responsive components (e.g., pH indicators), natural antimicrobial agents (e.g., plant polyphenols), and nano-enhancing materials (e.g., carbon quantum dots). These films enable multidimensional regulation of spoilage factors in protein-based foods. Based on the applied technological strategies, related studies can be classified into three major categories: intelligent monitoring type, antimicrobial-barrier type, and nano-enhanced type.

4.2.1Intelligent Monitoring SA Composite Films

Intelligent monitoring SA-based composite films can achieve fluorescence response and real-time freshness monitoring, thereby enhancing food safety. Chen et al.[60] developed an SA-pectin (PC)-Aronia melanocarpa anthocyanins (AMA)-tea polyphenol (TP) active packaging film for the preservation of Litopenaeus vannamei shrimp (Figure 5a). The results showed that the film exhibited a fluorescence response within the pH range of 6.8–7.5, with a color change from purple to blue, allowing real-time monitoring of shrimp freshness. The synergistic mechanism between AMA and TP enhanced the film's antimicrobial properties, with the inhibition zone diameter reaching 17.2 ± 0.03 mm. Furthermore, after 48 hours of storage, the total volatile basic nitrogen (TVB-N) content of shrimp packaged with the SA/PC/AMA/TP film remained at 18.67 ± 1.07 mg/100 g, which was 33% lower than that of the control group (27.77 ± 1.76 mg/100 g). After 60 hours of storage, the total viable count (TVC) of the shrimp packaged with the composite film was 5.66 ± 0.08 log CFU/g, while the TVC of the control group exceeded the safety limit of 6 log CFU/g after 48 hours. Similarly, An and Zhou[61] developed a colorimetric SA-agar-based film combined with a porous substrate to enhance its applicability in intelligent food packaging. This film could detect volatile amine compounds (e.g., trimethylamine) released during food spoilage, exhibiting a distinct color change. Experimental results showed that as the pH increased during storage, the film's color gradually shifted from red to orange, then to light orange, and finally to pale yellow-green, aiding consumers in visually assessing food quality. Additionally, the film's color variation correlated strongly with TVB-N levels, effectively monitoring shrimp spoilage.

4.2.2Antimicrobial-Barrier SA Composite Films

Antimicrobial-barrier SA-based composite films inhibit bacterial growth through controlled-release systems and minimize moisture loss via interfacial enhancement effects. Wang et al.[62] investigated the impact of tea polyphenol-modified SA-konjac glucomannan composite films on beef preservation (Figure 5b). The results indicated that, after 10 days of storage, the weight loss rate of beef packaged with the composite film was reduced by 46% compared to the control group, demonstrating superior moisture retention and enhanced sensory quality by maintaining the beef's bright red color. Additionally, after 10 days of storage, the TVC of beef packaged with the composite film was 1.39 log CFU/g, whereas the beef in the control group started to spoil after 8 days, with a TVC of 4.82 log CFU/g. Tong et al.[63] explored the effect of cinnamic acid incorporated into SA-pectin composite films on beef preservation. Their findings showed that, after 5 days of storage, the TVC of beef wrapped in the composite film was 84.09% lower than that of the control group, significantly reducing microbial contamination risk and effectively extending the beef's shelf life.

4.2.3Nano-Enhanced SA Composite Films

Nano-enhanced SA-based composite films utilize nanomaterials to improve food preservation performance. Jiang et al.[64] investigated the application of an SA-konjac glucomannan-nitrogen-doped carbon quantum dots (N-CQDs) composite film in the storage of Procambarus clarkii meat. The results demonstrated that N-CQDs enhanced interfacial adhesion, reduced moisture migration, and slowed oxidation rates. After 8 days of storage, the TVB-N content of P. clarkii meat packaged with the composite film remained below the safety threshold of 20 mg/100 g, with a TVC of 6.14 ± 0.39 log CFU/g, whereas the TVC of the polyethylene (PE) group exceeded 6.68 ± 0.31 log CFU/g after only 4 days. Additionally, after 8 days of storage, the thiobarbituric acid reactive substances (TBARS) value of P. clarkii meat packaged with the composite film was only 0.85 ± 0.03 mg/kg, significantly lower than that of the PE group (1.43 ± 0.04 mg/kg). Su et al.[Error! Reference source not found.] developed a colorimetric ammonia-sensing nanocomposite film based on starch/SA and Cu-Phe nanorods for monitoring the freshness of meat and aquatic products. The results indicated that this film exhibited a pronounced color change in response to ammonia, shifting from green to deep blue within the pH range of 6.8–9.2. When the TVB-N content exceeded 20 mg/100 g, the film provided real-time visual detection of shrimp and meat spoilage.

In summary, intelligent monitoring, antimicrobial-barrier, and nano-enhanced SA-based composite films have demonstrated promising potential in the preservation of meat and aquatic products. However, current studies still face challenges in industrial application, including process optimization, packaging cost control, and food contact safety evaluation. Future research should focus on long-term stability testing based on food safety standards, precise controlled-release mechanisms of antimicrobial agents, and the commercialization of intelligent packaging, ultimately promoting the widespread application of SA composite films in the food packaging industry.

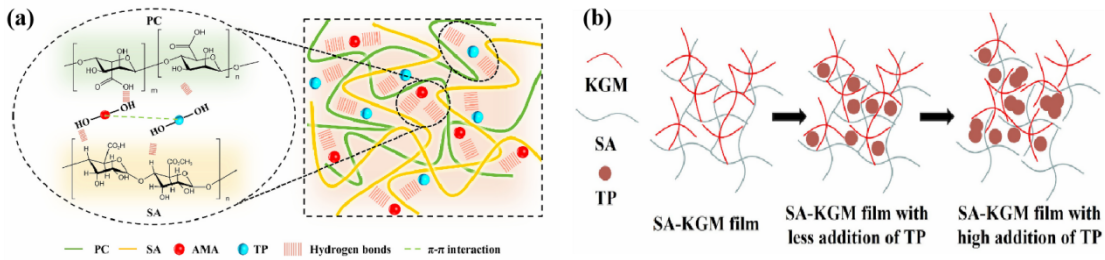

Fig.5 a Mechanistic diagram of sodium alginate-pectin-black fruit glandular rib anthocyanin-tea polyphenol composite membrane[61]; b Mechanism diagram of tea polyphenol-modified sodium alginate-konjac glucan composite membrane[62]

. Conclusion and Future Perspectives

Significant progress has been made in the application of sodium alginate (SA) composite films in the food packaging sector. However, challenges remain in practical implementation and industrialization, including the need for further optimization of mechanical properties, improved barrier performance, enhanced environmental stability, cost reduction, and scalable manufacturing. To address these issues, future research should focus on the following aspects to enhance the performance of SA composite films and facilitate their commercialization.

(1) Green and Sustainable Fabrication Processes

With the growing emphasis on green manufacturing and sustainable development, the fabrication of SA composite films should prioritize environmental friendliness, energy efficiency, and high productivity. Future research could explore the use of novel green solvents, such as ionic liquids and deep eutectic solvents (DESs),

to improve film dissolution and processing performance while minimizing the environmental impact of organic solvents. Additionally, optimizing advanced fabrication techniques, such as electrospinning, could enhance film uniformity, structural control, and production efficiency, thereby promoting large-scale manufacturing. The development of biodegradable or recyclable packaging systems, such as compostable SA films, could help mitigate environmental pollution from packaging waste. Furthermore, integrating enzymatic degradation technologies or biodegradation strains may provide more efficient degradation pathways, achieving truly sustainable food packaging solutions.

(2) Development of Smart Functional Packaging Films

Smart food packaging is an emerging trend in the food industry, and SA composite films can be functionally modified to incorporate intelligent features for food quality monitoring and shelf-life extension. Future research could integrate pH indicators, temperature-responsive materials, and gas sensors to develop packaging films capable of real-time freshness monitoring. For instance, natural pigments such as anthocyanins and curcumin could be introduced to enable visual detection of food spoilage based on color changes under different pH conditions. Additionally, combining SA films with nanosensing technology could lead to the development of intelligent packaging that detects variations in oxygen, carbon dioxide, or ethylene concentrations, thereby enhancing food storage safety.

(3) Industrialization and Regulatory Standardization

The industrialization of SA composite films is still in its early stages, and further research is needed to accelerate their transition into real-world applications. Future efforts should focus on developing cost-performance optimization models to balance film performance with production costs, thereby enhancing market competitiveness. Additionally, food contact safety assessments should be prioritized, ensuring compliance with regulatory standards established by the U.S. Food and Drug Administration (FDA), the European Food Safety Authority (EFSA), and the Chinese National Food Safety Standards (GB). Standardization efforts in food packaging regulations will be essential for the widespread adoption of SA-based packaging materials.

As a sustainable and functional food packaging material, SA composite films hold immense potential for future research and applications. With continuous advancements in materials science, nanotechnology, and smart packaging technologies, SA composite films are expected to play a more prominent role in the food packaging industry, offering innovative solutions for food safety, environmental protection, and sustainable development.

References

[1] Yan, H.; Wang, J.; Du, C.; Li, Z.; Yuan, H.; Xu, Z.; Tan, Y. Hydrogen Bond Mediated Strong Plasticization for High Performance Alginate Plastics. *Adv. Mater.* **2024**, 2400648.

[2] Ureña, M.; Phùng, T. T.-T.; Gerometta, M.; De Siqueira Oliveira, L.; Chanut, J.; Domenek, S.; Dole, P.; Roudaut, G.; Lagorce, A.; Karbowiak, T. Potential of Polysaccharides for Food Packaging Applications. Part 1/2 : An Experimental Review of the Functional Properties of Polysaccharide Coatings. *Food Hydrocolloids* **2023**, *144*, 108955.

[3] Hadi, A.; Nawab, A.; Alam, F.; Zehra, K. Physical, Mechanical, Optical, Barrier, and Antioxidant Properties of Sodium Alginate–Aloe Vera Biocomposite Film. *J. Food Process. Preserv.* **2021**, *45* (5).

[4] Yan, P.; Lan, W.; Xie, J. Modification on Sodium Alginate for Food Preservation: A Review. *Trends Food Sci. Technol.* **2024**, *143*, 104217.

[5] Doh, H.; Dunno, K. D.; Whiteside, W. S. Preparation of Novel Seaweed Nanocomposite Film from Brown Seaweeds Laminaria Japonica and Sargassum Natans. *Food Hydrocolloids* **2020**, *105*, 105744.

[6] Amaregouda, Y.; Kamanna, K. Carboxymethyl Cellulose/Starch-Based Films Incorporating Chitosan Nanoparticles for Multifunctional Food Packaging. *Cellulose* **2024**, *31* (4), 2413–2427.

[7] Tran, T. T. B.; Roach, P.; Nguyen, M. H.; Pristijono, P.; Vuong, Q. V. Development of Biodegradable Films Based on Seaweed Polysaccharides and Gac Pulp (Momordica Cochinchinensis), the Waste Generated from Gac Oil Production. *Food Hydrocolloids* **2020**, *99*, 105322.

[8] Zhang, M.; Chen, H. Development and Characterization of Starch sodium Alginate-Montmorillonite Biodegradable Antibacterial Films. *International Journal of Biological Macromolecules* **2023**, *233*, 123462.

[9] Puscaselu, R.; Gutt, G.; Amariei, S. Biopolymer-Based Films Enriched with Stevia Rebaudiana Used for the Development of Edible and Soluble Packaging. *Coatings* **2019**, *9* (6), 360.

[10] Saswat, O.; Maheshwari, P. H. Development of Biodegradable Calcium Alginate Films for Packaging Applications. *Emergent Materials* **2023**, *6* (1), 197–209.

[11] Marangoni Júnior, L.; Rodrigues, P. R.; Da Silva, R. G.; Vieira, R. P.; Alves, R. M. V. Sustainable Packaging Films Composed of Sodium Alginate and Hydrolyzed Collagen: Preparation and Characterization. *Food Bioprocess Technol.* **2021**, *14* (12), 2336–2346.

[12] Singh, A.; Singh, N.; Kaur, N. Design, Synthesis, and Antimicrobial Activity of Biodegradable Sodium Alginate/COF Polymeric Films for Smart Monitoring of Food Spoilage and Active Food Packaging. *ACS Food Sci. Technol.* **2024**, *4* (9), 2233–2243.

[13] Huang, J.; Zajforoushan Moghaddam, S.; Thormann, E. Structural Investigation of a Self-Cross-Linked Chitosan/Alginate Dialdehyde Multilayered Film with in Situ QCM-D and Spectroscopic Ellipsometry. *ACS Omega* **2019**, *4* (1), 2019–2029.

[14] Chen, H.; Lan, X.; Zhang, S.; Zhang, Q.; Zhang, X.; Chi, H.; Meng, Q.; Fan, F.; Tang, J. Properties of Gelatin-Zein Films Prepared by Blending Method and Layer-by-Layer Self-Assembly Method. *Int. J. Biol. Macromol.* **2025**, *292*, 139172.

[15] Liu, Z.; Liu, Q.; Lin, L.; Wang, Q.; Ma, W.; Cheng, Q.; Yang, J.; Tang, F.; Xu, M.; Yang, X.; Shang, H.; Wu, H. Stepwise Reinforcement Strategy for Guar Gum/Sodium Alginate Based Films: Introduction of Carboxylated Cellulose Nanofibers by Different Methods and Further Calcium Ion Crosslinking. *Food Hydrocolloids* **2024**, *156*, 110266.

[16] Kiattijiranon, P.; Auras, R. A.; Sane, A. Enhanced Functional Properties for Packaging Applications Using Sodium Alginate/Starch Bilayer and Multilayer Films. *ACS Applied Polymer Materials* **2024**, acsapm.4c00224.

[17] Shan, P.; Wang, K.; Yu, F.; Yi, L.; Sun, L.; Li, H. Gelatin/Sodium Alginate Multilayer Composite Film Crosslinked with Green Tea Extract for Active Food Packaging Application. *Colloids Surf. A* **2023**, *662*, 131013.

[18] Wang, H.; Gong, X.; Miao, Y.; Guo, X.; Liu, C.; Fan, Y.-Y.; Zhang, J.; Niu, B.; Li, W. Preparation and Characterization of Multilayer Films Composed of Chitosan, Sodium Alginate and Carboxymethyl Chitosan-ZnO Nanoparticles. *Food Chemistry* **2019**, *283*, 397–403.

[19] Yutong, C.; Yana, L. Development of multilayer films based on PLA/PBAT and sodium alginate for active packaging. *J. Food Saf.* **2024**, *44* (2), e13121.

[20] Shah, Y. A.; Bhatia, S.; Al-Harrasi, A.; Khan, T. S. Chitosan/Sodium Alginate/Ethyl Cellulose-Based Multilayer Film Incorporated with l-Ascorbic Acid for Improved Barrier and Antioxidant Properties. *International Journal of Biological Macromolecules* **2025**, *284*, 138169.

[21] Tian, J.; Deng, H.; Huang, M.; Liu, R.; Yi, Y.; Dong, X. Electrospun Nanofibers for Food and Food Packaging Technology. In *Electrospinning: Nanofabrication and Applications*; Elsevier, 2019; pp 455–516.

[22] Yuan, W.; Lee, H. W.; Yuk, H.-G. Antimicrobial Efficacy of Cinnamomum Javanicum Plant Extract against Listeria Monocytogenes and Its Application Potential with Smoked Salmon. *International Journal of Food Microbiology* **2017**, *260*, 42–50.

[23] Salević, A.; Prieto, C.; Cabedo, L.; Nedović, V.; Lagaron, J. M. Physicochemical, Antioxidant and Antimicrobial Properties of Electrospun Poly(ε-Caprolactone) Films Containing a Solid Dispersion of Sage (Salvia Officinalis L.) Extract. *Nanomaterials* **2019**, *9* (2), 270.

[24] Dede, S.; Sadak, O.; Didin, M.; Gunasekaran, S. Basil Oil-Loaded Electrospun Biofibers: Edible Food Packaging Material. *Journal of Food Engineering* **2022**, 319, 110914.

[25] Castellano, M.; Alloisio, M.; Darawish, R.; Dodero, A.; Vicini, S. Electrospun Composite Mats of Alginate with Embedded Silver Nanoparticles: Synthesis and Characterization. *J. Therm. Anal. Calorim*. **2019**, 137 (3), 767–778.

[26] Surendhiran, D.; Cui, H.; Lin, L. Encapsulation of Phlorotannin in Alginate/PEO Blended Nanofibers to Preserve Chicken Meat from Salmonella Contaminations. *Food Packaging and Shelf Life* **2019**, *21*, 100346.

[27] Amjadi, S.; Almasi, H.; Ghorbani, M.; Ramazani, S. Preparation and Characterization of TiO_2NPs and Betanin Loaded Zein/Sodium Alginate Nanofibers. *Food Packaging and Shelf Life* **2020**, *24*, 100504.

[28] Aloma, K. K.; Sukaryo, S.; Fahlawati, N. I.; Dahlan, K.; Oemar, S. Synthesis of Nanofibers from Alginate polyvinyl Alcohol Using Electrospinning Methods. *Macromol. Symp.* **2020**, *391* (1), 1900199.

[29] Giz, A. S.; Berberoglu, M.; Bener, S.; Aydelik-Ayazoglu, S.; Bayraktar, H.; Alaca, B. E.; Catalgil-Giz, H. A Detailed Investigation of the Effect of Calcium Crosslinking and Glycerol Plasticizing on the Physical Properties of Alginate Films. *International Journal of Biological Macromolecules* **2020**, *148*, 49–55.

[30] Ruan, P.; Zhang, K.; Zhang, W.; Kong, Y.; Zhou, Y.; Yao, B.; Wang, Y.; Wang, Z. Polyphenolic Truxillic Acid Crosslinked Sodium Alginate Film with Notable Antimicrobial and Biodegradable Properties for Food Packaging. *International Journal of Biological Macromolecules* **2024**, *279*, 135184.

[31] He, J.; Yang, S.; Goksen, G.; Cong, X.; Rizwan Khan, M.; Zhang, W. Functionalized Pectin/Alginate Food Packaging Films Based on Metal-Phenol Networks. *Food Bioscience* **2024**, *58*, 103635.

[32] Zhang, L.; Wang, C.; Huang, Y.; Wu, M. A Green, Facile, and Scalable Method for Fabricating High-Strength, Water-Resistant CNF/SA Composite Films. *ACS Sustainable Chem. Eng.* **2025**, acssuschemeng.4c09878.

[33] Liu, Y.; Zhang, Y.; Zhen, M.; Wu, Y.; Ma, M.; Cheng, Y.; Jin, Y. Effect of Catechin and Tannins on the Structural and Functional Properties of Sodium Alginate/Gelatin/ Poly(Vinylalcohol) Blend Films. *Food Hydrocolloids* **2023**, *135*, 108141.

[34] Choi, I.; Lee, Y.; Lyu, J. S.; Lee, J.-S.; Han, J. Characterization of Ionically Crosslinked Alginate Films: Effect of Different Anion-Based Metal Cations on the Improvement of Water-Resistant Properties. *Food Hydrocolloids* **2022**, *131*, 107785.

[35] Ramakrishnan, R.; Kulandhaivelu, S. V.; Roy, S.; Viswanathan, V. P. Characterisation of Ternary Blend Film of Alginate/Carboxymethyl Cellulose/Starch for Packaging Applications. *Industrial Crops and Products* **2023**, *193*, 116114.

[36] Marangoni Júnior, L.; Fozzatti, C. R.; Jamróz, E.; Vieira, R. P.; Alves, R. M. V. Biopolymer-Based Films from Sodium Alginate and Citrus Pectin Reinforced with SiO_2. *Materials* **2022**, *15* (11), 3881.

[37] Li, Y.; Qiu, C.; Qi, Y.; Yan, Y. Water Resistance Improvement of Sodium Alginate and Black Wolfberry Anthocyanins Based Films Treated by $CaCl_2$ for Food Packaging. *J. Oleo Sci.* **2025**, *74* (3), 275–285.

[38] Wu, D.; Wang, J.; Zhao, Y.; Li, S.; Yang, H.; Tan, R.; Zhang, T. Bio-Inspired Seaweed-Based Nanocomposite Materials with Excellent Degradability and Multifunctional Barrier Properties for Green Packaging. *Chemical Engineering Journal* **2024**, *479*, 147285.

[39] Kowalonek, J.; Łukomska, B.; Szydłowska-Czerniak, A. Color, Structure, and Thermal Stability of Alginate Films with Raspberry and/or Black Currant Seed Oils. *Molecules* **2025**, *30* (2), 245.

[40] Li, Y.; Shan, P.; Yu, F.; Li, H.; Peng, L. Fabrication and Characterization of Waste Fish Scale-Derived Gelatin/Sodium Alginate/Carvacrol Loaded ZIF-8 Nanoparticles Composite Films with Sustained Antibacterial Activity for Active Food Packaging. *International Journal of Biological Macromolecules* **2023**, *230*, 123192.

[41] Liu, S.; Li, Y.; Li, L. Enhanced Stability and Mechanical Strength of Sodium Alginate Composite Films. *Carbohydrate Polymers* **2017**, *160*, 62–70.

[42] Yu, K.; Yang, L.; Zhang, S.; Zhang, N.; Xie, M.; Yu, M. Stretchable, Antifatigue, and Intelligent Nanocellulose Hydrogel Colorimetric Film for Real-Time Visual Detection of Beef Freshness. *International Journal of Biological Macromolecules* **2024**, *268*, 131602.

[43] Hoque, M.; Babu, R. P.; McDonagh, C.; Jaiswal, S.; Tiwari, B. K.; Kerry, J. P.; Pathania, S. Pectin/Sodium Alginate-Based Active Film Integrated with Microcrystalline Cellulose and Geraniol for Food Packaging Applications. *International Journal of Biological Macromolecules* **2024**, *271*, 132414.

[44] Li, H.; Liu, C.; Sun, J.; Lv, S. Bioactive Edible Sodium Alginate Films Incorporated with Tannic Acid as Antimicrobial and Antioxidative Food Packaging. *Foods* **2022**, *11* (19), 3044.

[45] Zhang, X.; Kang, J.; Hu, H.; Wang, H.; Liu, Z.; Zhou, W.; Zhang, X. Impacts of Tannin Inclusion on Fabrication, Characterization and Antioxidant Activity of Sodium Alginate-Silk Fibroin-Tannin Films and Their Application on Fresh-Cut Apple Packaging. *Food Bioscience* **2023**, *54*, 102897.

[46] Chen, J.; Wu, A.; Yang, M.; Ge, Y.; Pristijono, P.; Li, J.; Xu, B.; Mi, H. Characterization of Sodium Alginate-Based Films Incorporated with Thymol for Fresh-Cut Apple Packaging. *Food Control* **2021**, *126*, 108063.

[47] Yun, D.; Liu, J. Preparation, Characterization and Application of Active Food Packaging Films Based on Sodium Alginate and Twelve Varieties of Mandarin Peel Powder. *Foods* **2024**, *13* (8), 1174.

[48] Eltabakh, M.; Kassab, H.; Badawy, W.; Abdin, M.; Abdelhady, S. Active Bio-Composite Sodium Alginate/Maltodextrin Packaging Films for Food Containing Azolla Pinnata Leaves Extract as Natural Antioxidant. *J Polym Environ* **2022**, *30* (4), 1355–1365.

[49] Zhang, X.; Li, X.; Zhang, H.; Jiang, S.; Sun, M.; He, T.; Zhang, T.; Wu, W. Self-Supporting Noncovalent Choline Alginate/Tannic Acid/Ag Antibacterial Films for Strawberry Preservation. *Int. J. Biol. Macromol.* **2024**, *265*, 130936.

[50] Srichaiyapol, O.; Maddocks, S. E.; Thammawithan, S.; Daduang, S.; Klaynongsruang, S.; Patramanon, R. TA-AgNPs/Alginate Hydrogel and Its Potential Application as a Promising Antibiofilm Material against Polymicrobial Wound Biofilms Using a Unique Biofilm Flow Model. *Microorganisms* **2022**, *10* (11), 2279.
[51] Song, B.; Zhang, T.; Yang, K.; Tian, G.; Dang, Y.; Ma, J. Zn^{2+} Ions Cross-Linking Sodium Alginate Encapsulated Bacterial Cellulose/ZnO Composite Film for Antibacterial Application. *Cellulose* **2023**.
[52] Zhang, X.; Zhang, B.; Mao, R.; Huang, Z.; Jing, K.; Jin, C.; Yang, B.; Qi, J.; Yu, M.; Xiong, G.; Hu, Y. A Novel Multilayer Film Based on Sodium Alginate/k-Carrageenan-Gelatin Incorporated with ZnO Nanoparticles and Oregano Essential Oil for Active Food Packing. *Progress in Organic Coatings* **2024**, *187*, 108170.
[53] Tang, S.; Wang, Z.; Li, P.; Li, W.; Li, C.; Wang, Y.; Chu, P. K. Degradable and Photocatalytic Antibacterial Au-TiO2/Sodium Alginate Nanocomposite Films for Active Food Packaging. *Nanomaterials* **2018**, *8* (11), 930.
[54] Yang, Z.; Zhai, X.; Li, M.; Li, Z.; Shi, J.; Huang, X.; Zou, X.; Yan, M.; Qian, W.; Gong, Y.; Holmes, M.; Povey, M.; Xiao, J. Saccharomyces Cerevisiae-Incorporated and Sucrose-Rich Sodium Alginate Film: An Effective Antioxidant Packaging Film for Longan Preservation. *International Journal of Biological Macromolecules* **2022**, *223*, 673–683.
[55] Thivya, P.; Bhosale, Y. K.; Anandakumar, S.; Hema, V.; Sinija, V. R. Development of Active Packaging Film from Sodium Alginate/Carboxymethyl Cellulose Containing Shallot Waste Extracts for Anti-Browning of Fresh-Cut Produce. *International Journal of Biological Macromolecules* **2021**, *188*, 790–799.
[56] El-Basiouny, N. M.; Soliman, S. M. A.; Khalil, N. M.; Abd El-Ghany, M. N. Chitosan and Alginate/Aspergillus Flavus-Mediated Nanocomposite Films for Preservation of Postharvest Tomatoes. *International Journal of Biological Macromolecules* **2025**, *297*, 139559.
[57] Ruchika; Sharma, S. K.; Kumar, R.; Yadav, S. K.; Saneja, A. Development of a Multifunctional and Sustainable Pterostilbene Nanoemulsion Incorporated Chitosan-Alginate Food Packaging Film for Shiitake Mushroom Preservation. *International Journal of Biological Macromolecules* **2025**, *293*, 139241.
[58] Chen, J.; Zhang, Y.; Liu, H.; Lu, H.; Xu, X.; Shen, M. Sodium Alginate-Camellia Seed Cake Protein Active Packaging Film Cross-Linked by Electrostatic Interactions for Fruit Preservation. *International Journal of Biological Macromolecules* **2025**, *288*, 138627.
[59] Farousha, K.; Rangaraj, V. M.; Mazumder, J. A.; Haija, M. A.; Banat, F. Date Seed Extract Encapsulated-MCM-41 Incorporated Sodium Alginate/Starch Biocomposite Films for Food Packaging Application. *International Journal of Biological Macromolecules* **2024**, *282*, 136785.
[60] Chen, S.; Zhang, H.; Jiang, Z.; Ding, X.; Chen, W.; Ma, N.; Xu, S.; Yang, L. Intelligent Active Packaging of Sodium Alginate and Pectin Mixed with Aronia Melanocarpa Anthocyanins and Tea Polyphenols for Shrimp Freshness Monitoring and Preservation. *International Journal of Biological Macromolecules* **2024**, *283*, 137754.
[61] An, N.; Zhou, W. Sodium Alginate/Ager Colourimetric Film on Porous Substrate Layer: Potential in Intelligent Food Packaging. *Food Chemistry* **2024**, *445*, 138790.
[62] Wang, S.; Li, M.; He, B.; Yong, Y.; Zhu, J. Composite Films of Sodium Alginate and Konjac Glucomannan Incorporated with Tea Polyphenols for Food Preservation. *International Journal of Biological Macromolecules* **2023**, *242*, 124732.
[63] Tong, W. Y.; Ahmad Rafiee, A. R.; Leong, C. R.; Tan, W.-N.; Dailin, D. J.; Almarhoon, Z. M.; Shelkh, M.; Nawaz, A.; Chuah, L. F. Development of Sodium Alginate-Pectin Biodegradable Active Food Packaging Film Containing Cinnamic Acid. *Chemosphere* **2023**, *336*, 139212.
[64] Jiang, Z.; Feng, J.; Dai, Y.; Yu, W.; Bai, S.; Bai, C.; Tu, Z.; Guo, P.; Liao, T.; Qiu, L. Preparation of a Biodegradable Packaging Film by Konjac Glucomannan/Sodium Alginate Reinforced with Nitrogen-Doped Carbon Quantum Dots from Crayfish Shell for Crayfish Meat Preservation. *International Journal of Biological Macromolecules* **2025**, *297*, 139596.
[65] Su, M.; Qin, H.; Tang, Q.; Peng, D.; Li, H.; Zou, Z. Colorimetric Ammonia-Sensing Nanocomposite Films Based on Starch/Sodium Alginate and Cu-Phe Nanorods for Smart Packaging Application. *International Journal of Biological Macromolecules* **2024**, *282*, 137470.