

Research Progress and Application of Biomass-Based Active and Intelligent Packaging in Food Preservation

Zhouqiao Liao *

Hangzhou No 2 High School Education Group Tianyuan Huilan School, Hangzhou, Zhejiang, China

* Corresponding Author Email: HBTY5861@outlook.com

Abstract. The problem of food waste and safety hazards caused by global resource corruption is prominent, and packaging technology has shifted from traditional passive barrier functions to the direction of "active preservation intelligent monitoring". This article analyzes the material system, active ingredients, preservation methods, and application of biomass-based active intelligent packaging materials suitable for different types of food. The research results in this paper show that lemon waste film, fenugreek gum, alginate, gelatin chitosan, cellulose and other biomass materials can achieve antibacterial, antioxidant and other functions by loading citral, rosemary essential oil, probiotic metabolites and other active ingredients. At present, there are relatively few packaging systems with intelligent monitoring capabilities, which can provide real-time feedback on food freshness. In practical applications, the shelf life of foods such as beef, chicken breast, tomatoes, strawberries, etc. has been extended by 30% -200%. Among them, the number of psychrophilic bacteria in chicken breast has decreased by 3.65 Log CFU/g, and the value of thiobarbituric acid reactants has decreased by 40% -60%. At the research and development level, there are still problems to be solved in this field, such as insufficient material mechanical properties, high costs, and difficulty in large-scale production.

Keywords: Biobased materials, active packaging, smart Monitoring, food Preservation, naturally active ingredients.

1. Introduction

Food corruption remains a global issue, with the FAO estimating 1.3 billion tons of food (one-third of global production) lost yearly due to spoilage—especially 30–50% losses in perishables like meat and aquatic products [1]. This causes over \$1 trillion in economic losses, wastes resources (water, energy), and risks foodborne illnesses from pathogens such as *Listeria monocytogenes* [2,3]. Traditional petroleum-based packaging (PE, PP) lacks active functions (e.g., microbial inhibition) and triggers "white pollution," creating an urgent need for sustainable, smart alternatives.

International studies focus on biomass carriers and natural active components: Alizadeh Ajayi et al. used lemon by-products to make double-layer films, extending beef shelf life to 12 days with pH-responsive monitoring [1]. Ramazanidoroh et al. applied probiotic metabolites to reduce chicken bacteria by 3.65 log CFU/g [4]. Domestic research leverages local resources (e.g., straw)—Zhou et al. developed cellulose films with 90% soil degradation and 99% *Vibrio* inhibition—but lags in multi-function integration and cost control.

Current challenges persist despite progress: material property balance, unstable active ingredients and unstandardized pH monitoring. This paper synthesizes recent advances in biomass-based smart packaging, compares international and domestic research focuses, and critically analyzes these core challenges. It further identifies priority directions—such as optimizing biomass-synthetic polymer ratios and establishing food-specific monitoring standards—to provide references for bridging research gaps and promoting industrial application of sustainable packaging.

2. Material System and Performance Control of Biomass Based Active Packaging

2.1. Natural Waste Source Materials

Biomass materials have the characteristics of renewability, degradability, and good biocompatibility, and have become the main carrier for active packaging. Different biomass materials can achieve a balance between mechanical properties and protective functions through their own structural characteristics or through material compounding. The use of agricultural waste to prepare packaging materials with both environmental friendliness and cost advantages has become a development trend in the industry. Typical applications include preparing packaging films from waste materials such as lemon processing waste and fenugreek seed gum. Lemon processing waste (with a pectin content of 21.84%) is combined with beet red pigment (optimal concentration of 8%) to form an indicator layer. Polyvinyl alcohol (PVA) nanofibers loaded with citral (average diameter of $341.58 \pm 62.44\text{nm}$) are electrospun on the surface of the indicator layer to prepare a double-layer film that combines intelligent monitoring and active preservation functions. The mechanical properties of the double-layer membrane have been significantly improved, with a tensile strength of 9.49MPa and a fracture elongation of 21.12%. The antibacterial test showed that the diameter of the antibacterial zone against *Staphylococcus aureus* was 11mm, and the diameter of the antibacterial zone against *Escherichia coli* was 12mm, both larger than the single-layer lemon waste film (antibacterial zone diameter < 8mm). When applied to fresh beef packaging, beef spoilage (pH > 6.5) causes the film to change from red to yellow, achieving real-time freshness indication. At the same time, the slow release of citral extends the shelf life of beef to 12 days, and the thiobarbituric acid reactant (TBARS) value (lipid oxidation index) is lower than 0.3mg/kg, far lower than the 0.8mg/kg of traditional polyethylene (PE) packaging [1]. The adhesive substances (glucose 50.01%, xylose 11.06%, rhamnose 9.42%) extracted from fenugreek seeds can be used to prepare the composite membrane containing carboxymethyl cellulose (CMC) and rosemary essential oil (REO) [5]. When the amount of REO added reaches 3%, the water solubility of the membrane decreases from 29.8% to 22.86%, and the water vapor permeability (WVP) drops to $1.26 \times 10^{-10} \text{g} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, significantly improving the membrane's moisture resistance. The antibacterial test showed that the diameter of the inhibition zone of the membrane against *Escherichia coli* was 14.92mm, and the diameter of the inhibition zone against *Serratia* was 14.31mm [5]. After using it for apple preservation, the water loss rate of apples was less than 6% (compared to 10.37% in the control group) after 27 days, the chlorophyll degradation rate slowed down (retention rate > 85%), the preservation period was extended from 12 days to 30 days, and there was no shrinkage or decay on the surface of the apples [5]. The films made from such natural waste materials generally have brittleness problems and need to be improved by adding plasticizers such as glycerol. For example, adding 0.3g/g glycerol to lemon waste film can increase its elongation at break to 30% [1]. When the amount of glycerol added to the Huluba seed film is 20%, the flexibility is optimal, but excessive glycerol should be avoided as it can lead to a decrease in the film's barrier performance [5]

2.2. Polysaccharide Based Composite Materials

Alginate and gelatin chitosan are the most extensively studied polysaccharide-based carriers, both of which achieve the dual goals of improving mechanical properties and maintaining functionality through partial composite ion crosslinking. Edible coatings can be prepared by encapsulating mustard (GM) and radish (RT) sprout extracts with corn soluble protein/chitosan (particle size 200-300nm), and then combining them with a 2% alginate solution. The DPPH free radical scavenging rate of the RT extract group was 70%, and the antibacterial rates against *Bacillus cereus* (BAC) and *Salmonella enterica* were 90% and 85%, respectively [3]. Applying this coating to tomato preservation can reduce the respiration rate of tomatoes from $20 \text{mg CO}_2/(\text{kg} \cdot \text{h})$ to $12 \text{mg CO}_2/(\text{kg} \cdot \text{h})$, control the ethylene content below $0.1 \mu\text{L/L}$, extend the shelf life from 12 days to 30 days, and maintain tomato hardness at 8.5kg/cm^2 after 20 days (compared to 5.2kg/cm^2 in the control group) [3]. A double-layer

membrane was prepared by combining metabolites of *Lactobacillus plantarum* A10 (14mg/mL) with alginate chitosan. After crosslinking with calcium ions (Ca^{2+}), the tensile strength of the membrane reached 4.5MPa and the elongation at break decreased by 33.65% [4]. When used for packaging chicken breast meat, the metabolic products in the film slowly release organic acids (lactic acid, acetic acid), maintaining the pH inside the packaging at 5.0-5.5. Within 5 days, the number of psychrophilic bacteria in the chicken breast meat decreased by 3.65 Log CFU/g compared to the control group, and the hardness change was less than 10%, which was better than vacuum packaging (hardness change>30%) [4]. A composite film can be prepared using 8g cowhide gelatin, 2g shrimp shell chitosan, and 4mL guava leaf water alcohol extract (50/50 v/v) [6]. The transmittance of the film is 0.79, and the oxygen transmittance is $9.7 \times 10^{-18} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, both significantly better than pure gelatin film [6]. The phenolic substances in pomegranate leaves can inhibit the growth of aerobic mesophilic bacteria in beef. After 9 days, the increase in the number of aerobic mesophilic bacteria in beef was $5.08 \times 10^1 \text{ CFU/g}$, which was much lower than the control group's $5.47 \times 10^1 \text{ CFU/g}$. At the same time, it can inhibit myoglobin oxidation, maintain the beef's redness value (a value) from 12.58 to 16.86, and keep the beef bright red to avoid browning[6]. The main advantage of polysaccharide-based materials is good biocompatibility, but high water solubility, which requires cross-linking (such as alginate and CaCl_2 cross-linking) or compounding with hydrophobic materials (such as zein) to reduce the loss of active ingredients [3,4].

2.3. Cellulose-Based Intelligent Materials

Cellulose has the characteristics of a large specific surface area, modifiability, and complete degradability, making it an excellent intelligent packaging carrier that can achieve dual functions of "active protection+real-time monitoring". The pH-sensitive infectious material (bromophenol blue) and antibacterial agent chitosan were combined into cellulose nanofibers (CNF) by the solution blending method to prepare the CNF composite film [7]. The tensile strength of the membrane is 18MPa, the elongation at break is 35%, and the degradation rate in soil is >90% within 30 days [7]. When used for packaging aquatic products, the film turns yellow when fish decay and release ammonia gas ($\text{pH} > 6.5$), achieving a visible freshness indication. At the same time, the antibacterial rate against *Vibrio parahaemolyticus* reaches 99%, and the oxygen permeability is reduced by more than 40% compared to traditional PE films [7]. In addition, cellulose-based membranes can be made into nanofiber membranes through electrospinning, such as CNF polyethyleneimine (PEI) composite membranes with a specific surface area of $100 \text{ m}^2/\text{g}$ and a sustained release time of 15 days for loaded citral, which are suitable for preservation during long-distance transportation of aquatic products [7].

3. Natural Antibacterial Agent

Natural antibacterial agents are safer than synthetic antibacterial agents such as sorbic acid and are recognized as GRAS substances with a wide antibacterial spectrum. Common types include citral, rosemary essential oil, guava leaf extract, etc. Citral is a common natural active ingredient in lemon waste film, which exerts antibacterial effects by disrupting microbial cell membranes. Its hydrophilic end can penetrate the phospholipid bilayer of microbial cell membranes, causing leakage of cellular contents and inhibiting the growth of microorganisms such as *Vibrio parahaemolyticus* and *Staphylococcus aureus*. The minimum inhibitory concentrations (MIC) of citral against *Vibrio parahaemolyticus* and *Staphylococcus aureus* were 0.2mg/mL and 0.3mg/mL, respectively [1,8,9]. The PVA nanofiber membrane loaded with citral achieves slow release of citral through "nanopore controlled release", with a release rate of $0.05 \text{ mg/cm}^2/\text{d}$. The antibacterial rate against *Escherichia coli* in beef is 99.9%, and the sustained release time is up to 12 days, which can avoid the loss of active ingredients caused by one-time release [1].

Rosemary essential oil contains carnosic acid, rosmarinic acid, α -pinene and other components, and has antioxidant and antibacterial functions. The DPPH radical scavenging rate of phenolic substances is 91.5%, and terpenoid alcohols can damage microbial cell walls [5]. The total phenolic

content of the Huluba seed gum composite film containing 3% REO is 40.1mg GAE/g, which can delay apple lipid oxidation (apple malondialdehyde (MDA) content<0.3mg/kg), and the diameter of the inhibition zone against *Penicillium* is 14.2mm [5]. By combining it with modified atmosphere packaging (MAP, 30% CO₂+60% N₂+10% O₂), the shelf life of Atlantic perch slices can be extended from 8 days to 15 days, and the volatile base nitrogen (TVB-N) value can be maintained below 20mg/100g, far below the upper limit of fresh products of 30mg/100g [5]. The main application limitations of natural antibacterial agents are their volatility and oxidation. Although it can be improved by microencapsulation or nanofiber loading, it is prone to hydrogen bonding when combined with high protein, high-fat and other food matrices, resulting in reduced activity [1,5].

3.1. Probiotic Metabolites

Organic acids, bacteriocins, peptides, and other metabolites produced by probiotics such as *Lactobacillus plantarum* and *Streptococcus pentosus* have broad-spectrum, efficient, and safe bactericidal abilities, meeting consumers' demand for "no artificial additives" and "natural" labels. The minimum bactericidal concentration (MBC) and minimum inhibitory concentration (MIC) of metabolites isolated from *Lactobacillus plantarum* A10 against *Listeria monocytogenes* were 4.75mg/mL and 11.89mg/mL, respectively. The lactate content in this metabolite is 1.2mg/mL, which can reduce the bacterial cell membrane potential. Plant derived lactobacilli can inhibit bacterial cell wall synthesis. Combining it with alginate chitosan film for chicken breast packaging, the organic acid concentration is maintained at 0.8-1.0mg/mL through "pH responsive release" (triggered by ammonia gas generated by meat spoilage) to achieve microbial inhibition, while the polysaccharide component reduces muscle water loss (water loss rate<6%) [4]. After compounding chitosan film with metabolites of *Streptococcus pentosus*, the antibacterial rate against *Vibrio parahaemolyticus* in aquatic products reached 99%, extending the shelf life of aquatic products by 7 days and maintaining the freshness index K value below 60% (K value>80% in the ice storage control group) [4]. This type of ingredient combines "biocompatibility+multifunctionality", but the release rate needs to be controlled, otherwise excessive acetic acid can cause food flavor deterioration (such as sourness in chicken breast) [4]. The metabolites need to be stored at low temperatures, such as 4°C to maintain stability, which is not suitable for preserving food at room temperature [4].

3.2. Functional Modulators

Functional regulators adjust the gas composition and humidity inside the packaging to meet the preservation needs of different foods and delay the decay process. Composite alginate coating with sodium bicarbonate citric acid system (mass ratio 1:1), slowly releases carbon dioxide through chemical reaction, and maintains the concentration of carbon dioxide in the packaging at 8% -10%. This concentration can inhibit the growth of *Pseudomonas aeruginosa* in Atlantic perch slices (colony count<6 Log CFU/g within 15 days), while avoiding fish hardening caused by high carbon dioxide (hardness change rate<15%) [3]. Making citric acid into a starch-based "porous carrier" patch with a release rate of 0.1mg/h can maintain the humidity inside the strawberry packaging at 80% -85%, with a water loss rate of<5% (compared to 15% in the control group), effectively reducing strawberry wilting. The acidic environment (pH 4.0-4.5) extends the shelf life of strawberries to 18 days, with a gray mold infection rate of<10% (compared to 60% in the control group) and a vitamin C retention rate of>85% [10].

4. Comparison of Application Effects of 4 Different Food Categories

The active preservation effect of packaging is significantly affected by food moisture content, microbial sensitivity, respiration, and respiration rate. There are significant differences in the application strategies and effects of different categories of food. For meat, the core problem of spoilage is fatty acid decay and the growth of pathogenic bacteria such as *Listeria monocytogenes* and *Escherichia coli*. In response to this characteristic, the lemon waste film PVA nanofiber bilayer

film synergistically reduces the TBARS value of beef by 62.5% through the combination of "citral antioxidant + betarubicin monitoring", while achieving real-time feedback on freshness [1]. The probiotic metabolite film relies on the "organic acid antibacterial + polysaccharide water retention" mechanism to reduce the loss of moisture and microbial quantity in chicken breast meat, while ensuring that the tenderness and color of the meat are not affected. The key to such packaging is that the active ingredients only play a "local role" on the surface of the food, avoiding systemic ingestion by the human body [4]. In the preservation of fruits and vegetables, aerobic respiration, ethylene release, and mold growth are the main causes of spoilage. Therefore, different technical paths need to be adopted accordingly: alginate RT extract coating reduces ethylene production by inhibiting respiratory enzyme activity, huluba seed gel film reduces water and nutrient loss by "physical barrier water retention+essential oil antibacterial", citric acid patch inhibits strawberry mold by "humidity control+acidic environment" [3,5,10]. When applied, strategies need to be adjusted according to the respiratory characteristics of fruits and vegetables. For example, tomato and other climacteric fruits and vegetables need to focus on controlling ethylene content, while strawberry and other non-climacteric fruits and vegetables need to prioritize water retention [3,5,10]. For baking materials such as Yufuka dough, the main problems of spoilage are the growth of mold (*Penicillium* and *Aspergillus*), yeast contamination, and starch retrogradation. Polypropylene composite films containing 6% sorbic acid can inhibit mold growth through "sorbic acid slow-release" (inhibition zone diameter 6.7mm) and delay starch retrogradation (retrogradation rate reduced by 60%). The migration amount of sorbic acid in the film is less than 0.01mg/kg, which meets the GB 4806.7-2016 standard [2]. However, the preservation of other baked goods, such as bread, also needs to pay attention to the influence of humidity. Excessive humidity can easily cause film dissolution, and chemical cross-linking is needed to improve the water resistance of the film [2]. Aquatic products are prone to being polluted by *Vibrio parahaemolyticus* and *Pseudomonas* spp. Due to their moisture content >70%, and their decay rate is 2-3 times that of meat. Therefore, alginate can be combined with modified atmosphere packaging (MAP) to inhibit bacterial growth and oxidation through "carbon dioxide antibacterial+barrier protection" [11]. At the same time, clove essential oil can be used to form a membrane structure on the surface of aquatic products to destroy bacterial cell membranes and reduce the number of harmful bacteria [9]. During the application process, the oxygen content in the package needs to be strictly controlled to <0.1%, to avoid fish browning [7,9].

5. Challenges and Future Trends

Although significant progress has been made in biomass-based active intelligent packaging, there are still technical and application issues in the research and industrialization process. In terms of material performance balance, most biomass materials, such as alginate and fenugreek seed gum, have poor mechanical properties and need to be improved by compounding with materials such as PVA and chitosan. However, compounding can reduce material degradation. For example, after compounding alginate with PVA, the tensile strength is increased by 40%, but the degradation time is extended from 30 days to 60 days [3,4]. In terms of mobility and stability, the migration amount of synthetic antibacterial agents (such as malic acid) needs to be strictly controlled, while natural antibacterial agents (such as essential oils) are prone to volatilization and loss of activity. Although the migration amount of malic acid in Yufuka dough packaging meets the standard, its activity decreases after 30 days, and the inhibition rate drops from 90% to 70% [2]. In terms of large-scale production costs, processes such as microcapsule preparation and electrospinning can increase packaging costs by 30% -50% compared to traditional packaging. For example, the price of nano silver antibacterial film is 40% higher than that of PE film, which is difficult for small and medium-sized enterprises to afford [4,11]. In terms of missing standards, there is currently no unified standard for key indicators such as the release rate of active ingredients and the color change threshold. For example, the color change of beet red pigment corresponds to a pH range of 4-8, while there are differences in pH changes during food spoilage, which require targeted adjustments [1,11]. In

response to these issues, future research can be advanced from multiple directions, including the construction of an integrated system of "antibacterial antioxidant intelligent monitoring" (such as a three-layer film structure containing a pH indicator layer (beet red pigment), a carbon dioxide control layer (sodium bicarbonate), and an antibacterial layer (citral)) to meet the preservation needs of complex foods [1,3], the use of agricultural waste such as citrus peel, seed residue, and fruit and vegetable by-products to prepare packaging materials (such as lemon waste film, which has a raw material cost only one-third of PE film and can reduce waste emissions) [1,5], and the combination of radio frequency identification (RFID) technology with food traceability and dynamic monitoring (cellulose based RFID) Tags can monitor the temperature and oxygen concentration inside the packaging of cold chain food in real time, providing data support for food supply chain management [11], as well as design responsive release systems based on food spoilage kinetics (such as activating the release of active ingredients through ammonia gas generated by meat spoilage (pH triggered) or cold chain breakage (temperature triggered) to improve preservation efficiency) [4,10].

6. Conclusion

This study shows that biomass-based active intelligent packaging can effectively improve food preservation and environmental issues by combining natural materials with efficient active ingredients. Lemon waste film, alginate, cellulose and other biomass materials have achieved biodegradability in packaging, while active ingredients such as citral and probiotic metabolites balance preservation safety and effectiveness. When applied in foods such as meat, fruits and vegetables, aquatic products, etc., the shelf life is extended by 30% -200%. In the future, it is necessary to promote the industrialization of this technology through material modification, process optimization, and standard setting. With the increasing attention of consumers to food safety, biomass-based active intelligent packaging is expected to become the mainstream packaging technology in the food industry, providing a solution to the global food waste problem.

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