



Chitosan-Based Edible Coatings for Food Preservation: A Critical Review of Mechanisms, Applications, and Future Prespective

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Abstract

Chitosan-based edible coatings have emerged as one of the most promising bio-based preservation strategies for extending the shelf life of perishable foods. Owing to their biodegradability, biocompatibility, film-forming ability, and intrinsic antimicrobial activity, chitosan coatings have been extensively investigated as alternatives to synthetic preservatives in food systems. However, despite the growing number of studies reporting positive outcomes, the effectiveness of chitosan-based coatings remains highly variable across different food matrices, formulation strategies, and application methods. This variability highlights the need for a critical evaluation of the current literature rather than a descriptive summary of reported findings. Therefore, this review critically examines the physicochemical characteristics of chitosan and compares its primary preservation mechanisms, including antimicrobial activity, antioxidant function, and barrier performance. Furthermore, this review evaluates the comparative effectiveness of chitosan coatings in fruits, vegetables, meat, seafood, and dairy products, with emphasis on differences in food matrix responses, coating formulations, and preservation outcomes. Particular attention is given to the comparative performance of coating application methods, including spraying, dipping, and foaming/dripping systems, to assess their suitability for laboratory and industrial implementation. In addition, the role of chitosan modifications, including nanochitosan, bioactive incorporation, and composite coating systems, is critically discussed to identify current advances and technological limitations. Major research gaps remain in formulation standardization, sensory optimization, industrial scalability, and regulatory validation. Future research should focus on the development of multifunctional chitosan systems with improved physicochemical stability, enhanced consumer acceptability, and greater compatibility with sustainable food packaging technologies. Overall, this review provides a critical and comparative perspective on the current progress and future potential of chitosan-based edible coatings as sustainable materials for next-generation food preservation systems.

Keywords: antrimicrobial activity; bioactive; chitosan; critical review; edible coating; food preservation; nanochitosan

1. Introduction

Food preservation remains one of the most important challenges in modern food systems due to the high perishability of fresh and minimally processed products (Elsabee *et al.*, 2013). Fruits, vegetables, meat, seafood, and dairy products are highly susceptible to microbial contamination, oxidative deterioration, moisture loss, and physiological degradation during storage, all of which contribute to shortened shelf life, reduced nutritional value, and significant economic losses (Muñoz-Tebar *et al.*, 2023). Conventional preservation strategies such as refrigeration, thermal processing, modified atmosphere packaging, and synthetic preservatives have long been employed to mitigate these issues (Khezerlou *et al.*, 2023). How-

ever, these approaches are often associated with important limitations, including incomplete microbial control, nutrient degradation, environmental burden, and growing consumer concerns regarding the safety of synthetic additives (X. Liu et al., 2025). Among conventional preservation approaches, synthetic preservatives such as benzoates, nitrites, sulfites, and sorbates remain widely used due to their low cost and broad-spectrum antimicrobial effects (Liu et al., 2024). Nevertheless, increasing evidence regarding their potential toxicological effects, possible allergenicity, and long-term health concerns has intensified consumer demand for safer and more sustainable alternatives (Chaudhari et al., 2023). At the same time, the global food sector is under increasing pressure to reduce plastic waste, minimize food loss, and adopt environmentally responsible preservation technologies (Gaspar & Braga, 2023). These combined concerns have accelerated interest in biodegradable and bioactive materials capable of extending shelf life while maintaining food quality and safety (Saber et al., 2023).

In this context, edible coating technology has emerged as a promising postharvest and food preservation strategy (Miteluţ et al., 2021). Edible coatings are thin layers of consumable materials applied directly to food surfaces to act as semi-permeable barriers against moisture transfer, oxygen diffusion, solute migration, and microbial contamination (Liu et al., 2022). By modifying the immediate microenvironment surrounding the food surface, edible coatings can reduce respiration rates, delay oxidation, maintain textural integrity, and prolong the sensory and nutritional quality of perishable products (Vargas et al., 2008). In contrast to passive coatings that function mainly as physical barriers, active edible coatings can also serve as carriers of antimicrobial, antioxidant, and functional compounds, thereby providing enhanced preservation performance (Riseh et al., 2023).

Among the wide range of biopolymers investigated for edible coating applications, chitosan has gained particular attention due to its multifunctional physicochemical and biological properties (Elsabagh et al., 2023). Chitosan is a cationic polysaccharide derived from the partial deacetylation of chitin, a naturally abundant biopolymer primarily obtained from crustacean shells, fungal biomass, and other marine by-products (Khezerlou et al., 2023). Its biodegradability, biocompatibility, non-toxicity, and excellent film-forming ability make chitosan highly attractive for food preservation applications (Moreno et al., 2023). More importantly, chitosan possesses intrinsic antimicrobial and antioxidant properties, enabling it to function not only as a physical coating matrix but also as an active preservation agent (Tebar et al., 2023).

Over the past decade, a substantial number of studies have reported the successful application of chitosan-based edible coatings in extending the shelf life of fruits, vegetables, meat, seafood, and dairy products (Wang et al., 2021). These studies have demonstrated improvements in microbial stability, reduced oxidation, delayed ripening, and lower moisture loss (Hu et al., 2023). However, despite the growing body of literature, the reported preservative performance of chitosan coatings remains highly inconsistent across studies (Apriliyani et al., 2022). Variability in antimicrobial efficacy, barrier performance, and sensory outcomes is frequently observed due to differences in chitosan molecular weight, degree of deacetylation, concentration, solvent system, incorporation of active compounds, food matrix characteristics, and coating application methods (Hasanin et al., 2025). As a result, direct comparison across studies remains difficult, and the broader practical applicability of chitosan coatings is often overstated (Santiago et al., 2025).

Most published articles on chitosan-based edible coatings focus primarily on descriptive outcomes, often emphasizing positive preservation effects without critically comparing the experimental conditions responsible for such variability (Wang et al., 2024). While numerous review articles have summarized the antimicrobial and physicochemical properties of chitosan, fewer studies have critically examined the comparative influence of formulation strategies, food matrix interactions, and coating application methods on preservation performance (Liu et al., 2023). In particular, the relative advantages and limitations of different coating techniques, the role of nanochitosan and composite systems, and the barriers to industrial implementation remain insufficiently evaluated (Peng et al., 2025; Sharma et al., 2021).

Therefore, a critical and comparative review is necessary to move beyond descriptive reporting and establish a clearer understanding of the functional role, technological limitations, and practical potential of chitosan-based edible coatings in food preservation. This review critically examines the physicochemical basis of chitosan as a food-grade biopolymer and compares its major preservation mechanisms, including

antimicrobial, antioxidant, and barrier functions. In addition, this review evaluates the comparative effectiveness of chitosan coatings across different food matrices and application techniques, with particular emphasis on formulation-dependent performance and industrial relevance. Finally, current limitations, major research gaps, and future directions are discussed to provide a more comprehensive framework for the rational development of next-generation chitosan-based preservation systems.

2. Materials and Methods

This review was written by collecting and analyzing journal articles related to the use of chitosan as an edible coating for food preservation. The aim of this review was to compare previous studies and understand how chitosan works in maintaining food quality and extending shelf life (Elsabee & Abdou, 2013). The articles used in this review were collected from several scientific databases, including Scopus, ScienceDirect, PubMed, and Google Scholar. The search was carried out using keywords such as “chitosan”, “edible coating”, “food preservation”, and “nanochitosan”. Most of the selected articles were published between 2013 and 2025, in order to cover both fundamental and recent studies on chitosan-based edible coatings (X. Liu et al., 2023; Muñoz-Tebar et al., 2023).

Only peer-reviewed journal articles related to food preservation were included in this review. Studies were selected if they discussed chitosan as an edible coating or film and reported its effects on antimicrobial activity, antioxidant activity, barrier properties, shelf life, or food quality. Articles focusing on non-food applications, such as biomedical or pharmaceutical uses, were not included (Miteluț et al., 2021). After screening titles, abstracts, and full texts, more than 100 relevant journal articles were selected and reviewed. The selected studies were then compared based on food type, coating formulation, application method, and preservation results. This approach was used to make the discussion more analytical by comparing findings from different studies, rather than only summarizing them one by one (Saberī Riseh et al., 2023).

3. Chitosan As a Functional Biopolymer in Food Preservation

Chitosan is a natural polysaccharide produced through the deacetylation of chitin, a structural biopolymer commonly found in crustacean shells, fungal cell walls, and other natural sources. In food preservation, chitosan has gained considerable attention because it is biodegradable, non-toxic, biocompatible, and able to form thin films on food surfaces, making it suitable for edible coating applications (Abdou et al., 2013). Compared with other biopolymers used in edible coatings, chitosan is considered more functional because it does not only act as a physical barrier but also provides active protection. Many edible coating materials mainly function by reducing moisture and gas transfer, while chitosan offers additional antimicrobial and antioxidant effects that directly contribute to food preservation (Ma et al., 2024). This multifunctional role makes chitosan one of the most widely studied biomaterials in food coating systems.

One of the most important properties of chitosan is its film-forming ability. Chitosan can form a thin and transparent protective layer on the surface of food products, which helps reduce oxygen transfer, moisture evaporation, and exposure to external contaminants. This barrier function is important in slowing down respiration, oxidation, and surface dehydration, especially in fresh fruits and vegetables (Miteluț et al., 2021). Because of this, chitosan coatings are often used to maintain texture, color, and freshness during storage.

Another important characteristic of chitosan is the presence of amino groups in its structure. Under acidic conditions, these amino groups become positively charged and can interact with negatively charged microbial cell membranes. This interaction can damage the membrane structure, increase permeability, and eventually inhibit microbial growth (Santiago et al., 2025). This natural antimicrobial property is one of the main reasons chitosan is considered more effective than many other edible coating materials.

In addition to antimicrobial activity, chitosan also contributes to oxidation control. Several studies have shown that chitosan can help reduce oxidative deterioration by limiting oxygen exposure and scavenging free radicals, which is especially important in foods that are sensitive to pigment degradation, lipid oxida-

tion, and nutrient (Hasanin et al., 2025). This antioxidant role helps preserve the color, flavor, and nutritional quality of food products during storage.

Another advantage of chitosan is its flexibility in formulation. Chitosan can be combined with other active compounds such as essential oils, plant extracts, organic acids, and nanoparticles to improve coating performance. These modifications are often used to enhance antimicrobial strength, improve antioxidant capacity, and increase coating stability (Muñoz et al., 2023). Because of this flexibility, chitosan has become one of the most adaptable materials for active edible coating systems. Recent studies have also shown increasing interest in nanochitosan and composite chitosan systems. Compared with conventional chitosan, nanochitosan generally has a smaller particle size, larger surface area, and stronger interaction with microbial cells, which may improve preservation performance (Peng et al., 2025). This development shows that chitosan is no longer viewed only as a basic coating material, but also as a functional platform for the development of more advanced and active food preservation systems

4. Comparative Mechanisms of Chitosan in Food Preservation

The preservative effect of chitosan is generally associated with three main mechanisms, namely antimicrobial activity, antioxidant activity, and barrier properties. These mechanisms often work together, but their relative contribution can vary depending on the food matrix, formulation, and storage conditions (Adil-etta et al., 2021). Because of this, the preservative effect of chitosan is not caused by one mechanism alone, but by the combined action of several protective functions.

Among these mechanisms, antimicrobial activity is the most widely discussed. Chitosan contains positively charged amino groups that can interact with negatively charged microbial cell membranes, leading to membrane disruption, leakage of intracellular components, and inhibition of microbial growth (Usman et al., 2025). This mechanism is often reported as the main reason for shelf-life extension in highly perishable foods such as seafood, meat, and fresh-cut fruits, where microbial spoilage is one of the main causes of quality (Karimullah et al., 2024).

However, in fresh fruits and vegetables, several studies suggest that the barrier function of chitosan may be more important than its direct antimicrobial activity. Chitosan coatings can reduce oxygen transfer and water loss from the food surface, which helps slow respiration, delay ripening, and maintain firmness during storage (Jafarzadeh et al., 2021; Kaewklin et al., 2018). In this case, shelf-life extension is often more strongly related to moisture and gas regulation than to direct microbial inhibition.

Antioxidant activity is another important mechanism, although it is discussed less often than antimicrobial effects. Chitosan can reduce oxidative deterioration by limiting oxygen exposure and slowing the formation of free radicals. This function is particularly important in foods that are sensitive to oxidation, such as meat, seafood, and lipid-rich products, where oxidation contributes to rancidity, pigment degradation, and nutrient loss (Hasanin et al., 2025). In these products, antioxidant protection may contribute as much as antimicrobial activity to the overall preservation effect.

Several studies also show that the dominant mechanism of chitosan can change depending on the formulation used. In pure chitosan coatings, preservation mainly depends on the natural barrier and antimicrobial properties of chitosan itself. In contrast, modified coatings such as nanochitosan, composite films, and bioactive-loaded systems often show stronger multifunctional performance (Chaudhari et al., 2023). For example, nanochitosan has been reported to improve antimicrobial efficiency due to its smaller particle size and larger surface area, while coatings enriched with essential oils or plant extracts often show stronger antioxidant and antimicrobial effects (Liu et al., 2025).

Overall, current studies show that chitosan preserves food through multiple mechanisms rather than a single dominant pathway. Antimicrobial activity is often more important in foods prone to microbial spoilage, barrier properties are more influential in fresh produce, and antioxidant effects become more relevant in oxidation-sensitive foods. This explains why different studies often report different preservation outcomes even when the same coating material is used. Edible coatings are expected to play an important role in supporting sustainable food preservation and enhancing the availability of fresh and nutritious food.

5. Comparative Applications in Different Food Matrices

The effectiveness of chitosan-based edible coatings is strongly influenced by the type of food being treated. Although chitosan has shown promising preservative effects in many studies, its performance is not always consistent across different food matrices because each food has different physical, chemical, and microbiological characteristics (Dai et al., 2025). Therefore, the effectiveness of chitosan coatings should be evaluated according to the specific properties of each food group. In fruits, chitosan is widely used to delay ripening, reduce moisture loss, and maintain texture during storage. Several studies have shown that chitosan coatings can reduce respiration rate, slow ethylene production, and preserve firmness in fruits such as strawberries, apples, bananas, mangoes, tomatoes, and citrus (Hu et al., 2023). In most fruit systems, the preservative effect of chitosan is mainly related to barrier protection and delayed physiological deterioration rather than direct microbial inhibition (Alemu et al., 2025).

In vegetables, chitosan is mainly applied to maintain freshness and reduce postharvest quality loss. Similar to fruits, the barrier effect remains important in reducing water loss and slowing metabolic activity. However, in fresh-cut vegetables, antimicrobial activity becomes more important because tissue damage accelerates spoilage and increases contamination risk (Gammage et al., 2025). This indicates that even within plant-based foods, the dominant preservation role of chitosan may change depending on the level of processing.

In meat products, chitosan is commonly used to reduce microbial growth and delay lipid oxidation. Compared with fruits and vegetables, spoilage in meat is more strongly associated with bacterial contamination and oxidative rancidity. Therefore, the antimicrobial and antioxidant functions of chitosan are more important than its barrier effect in meat preservation (Bastomyet al., 2025). Several studies have reported that chitosan coatings can reduce total microbial count, preserve color stability, and slow rancidity in fresh and processed meat products (Hasanin et al., 2025).

A similar trend is observed in seafood, where chitosan is frequently used to reduce microbial spoilage and maintain quality during chilled storage. Seafood is highly perishable due to its high moisture content, high protein availability, and rapid microbial growth. In this food group, chitosan has been shown to reduce microbial load, delay protein degradation, and maintain sensory quality in fish fillets, shrimp, and shellfish products (Santos et al., 2020). Compared with fresh produce, the antimicrobial role of chitosan is generally more dominant in seafood preservation.

In dairy products, the use of chitosan-based coatings is less frequently reported but still shows potential. Chitosan has been investigated in cheese and fermented dairy products to reduce surface contamination, control moisture loss, and improve storage stability. However, compared with other food groups, dairy applications remain more limited and often show less consistent results, partly due to differences in pH, fat composition, and sensory sensitivity (Iqbal et al., 2025).

Overall, current studies show that the performance of chitosan-based coatings cannot be generalized across all food systems. In fruits and vegetables, chitosan mainly acts by slowing physiological deterioration and reducing moisture loss, whereas in meat and seafood its effectiveness is more strongly related to antimicrobial and antioxidant protection. This difference explains why the same chitosan formulation may produce different preservation outcomes depending on the food matrix.

6. Comparative Applications in Different Food Matrices

The effectiveness of chitosan-based edible coatings is not only influenced by formulation and food type, but also by the method used to apply the coating. Different application methods can affect coating thickness, surface uniformity, material loss, and overall preservation performance (Andrade et al., 2012). For this reason, the choice of coating method is an important factor in determining the practical effectiveness of chitosan-based preservation systems.

Dipping is one of the most commonly used methods in laboratory-scale studies because it is simple, inexpensive, and able to cover the entire surface of the food product. In this method, food is immersed

directly into the coating solution and then removed for drying. This allows relatively complete coating coverage, which is useful in small-scale experimental studies (Adiletta et al., 2021). However, dipping often produces thicker and less uniform coating layers, and excessive solution retention may affect texture and appearance, especially in delicate products.

Spraying is often considered more suitable for industrial application because it allows better control of coating thickness and more uniform distribution on the product surface. Compared with dipping, spraying generally uses less coating solution and can reduce material waste, making it more efficient for large-scale processing (Jafarzadeh et al., 2021). However, spraying requires specialized equipment and process optimization, and uneven atomization may reduce coating consistency if processing conditions are not properly controlled.

Foaming and dripping methods are less commonly used but have been explored as alternative coating techniques. These methods are generally considered more economical because they can reduce coating solution consumption and may be useful for selected products such as fruits with larger surfaces. However, compared with dipping and spraying, these methods are less frequently studied and often show lower coating uniformity (Guerra et al., 2024). As a result, their practical use in food preservation remains limited. Overall, dipping is the most practical method for laboratory-scale experiments, while spraying is generally more suitable for industrial-scale application due to better control and efficiency. Foaming and dripping methods may offer economic advantages, but their lower coating consistency and limited validation currently reduce their practical relevance. This suggests that coating performance depends not only on the material itself, but also on how effectively it is applied to the food

7. Current Limitations and Research Gaps

Although chitosan-based edible coatings have shown promising results in many studies, several important limitations still restrict their wider application in food preservation systems. One of the main limitations is the lack of formulation standardization. The effectiveness of chitosan coatings is strongly influenced by several formulation parameters, including molecular weight, degree of deacetylation, concentration, pH, and solvent type (Dai et al., 2025). Because these parameters vary widely across studies, the reported preservation performance is often inconsistent, making it difficult to directly compare results or identify the most effective formulation. This lack of standardization remains one of the major obstacles in translating laboratory findings into practical applications.

Another major limitation is related to sensory quality and consumer acceptance. Although chitosan coatings are effective in slowing spoilage, several studies have reported that coating application may alter the sensory properties of food, including texture, gloss, flavor, aroma, and mouthfeel. These changes are more frequently observed when high concentrations of chitosan are used or when strong bioactive additives such as essential oils are incorporated into the coating system (Koyuncu, 2025). As a result, although antimicrobial performance may improve, consumer acceptance may decline, which creates an important trade-off between preservation efficiency and product acceptability.

The stability of chitosan-based coatings during storage is another limitation that is often overlooked. Several studies report that coating performance may decrease over time due to structural instability, changes in viscosity, poor adhesion, or uneven coating distribution during storage and handling. This issue becomes more significant in composite and bioactive-loaded systems, where interactions between chitosan and added compounds may affect coating integrity and functional performance (Alemu et al., 2025). This suggests that good antimicrobial activity alone is not sufficient if the coating system lacks physical stability during real storage conditions. Industrial scalability also remains a major research gap. Most studies on chitosan-based edible coatings are still conducted at laboratory scale using small sample sizes, controlled environments, and short storage periods. While these studies are useful for understanding coating behavior, they do not fully represent industrial conditions such as large-volume production, processing variability, equipment limitations, and commercial distribution systems (Hasanin et al., 2025; Jiménez-

Gómez & Cecilia, 2020; Khezerlou et al., 2023), Because of this, the industrial feasibility of many reported chitosan formulations remains uncertain.

Another important limitation is the limited economic evaluation of chitosan-based preservation systems. Although chitosan is often described as a low-cost and sustainable material, relatively few studies provide detailed economic analysis related to raw material sourcing, extraction cost, formulation cost, processing efficiency, and commercial scalability. This is particularly relevant for modified systems such as nanochitosan and composite coatings, which may offer better performance but also require more expensive processing and formulation steps (Iqbal et al., 2025; Resende et al., 2019). Without cost evaluation, the practical value of these advanced systems remains difficult to justify for commercial food applications.

Regulatory and safety aspects also remain underexplored. Although chitosan is generally recognized as a safe biopolymer, fewer studies have discussed regulatory approval, labeling requirements, allergen concerns, and long-term safety, especially for nanochitosan and active composite systems (Peng et al., 2025; Prieto-Santiago et al., 2025). This issue is particularly important because industrial adoption depends not only on technical performance but also on regulatory compliance and consumer safety assurance. Overall, current studies show that the major limitations of chitosan-based edible coatings are not only related to preservative performance, but also to formulation consistency, sensory quality, physical stability, industrial feasibility, economic practicality, and regulatory validation. These limitations explain why chitosan remains highly promising in laboratory research but still faces several barriers before wider commercial implementation can be achieved.

8. Future Perspective

Future development of chitosan-based edible coatings should focus not only on improving preservative performance, but also on increasing their practical applicability in real food systems. Although many studies have shown promising results, future research needs to move beyond laboratory-scale optimization and focus more on formulation consistency, industrial feasibility, and consumer acceptance (Moreno et al., 2025; Khezerlou et al., 2023; Usman et al., 2025). One important direction is the development of more standardized chitosan formulations. Future studies should place greater emphasis on controlling key parameters such as molecular weight, degree of deacetylation, concentration, and solvent conditions in order to improve reproducibility and allow better comparison between studies. Better formulation standardization is important not only for improving consistency, but also for making results easier to translate into industrial systems (Dai et al., 2025; Manera et al., 2011).

Another promising direction is the development of multifunctional coatings through the incorporation of active compounds such as essential oils, plant extracts, probiotics, and natural antioxidants. These additives may improve antimicrobial and antioxidant performance while also expanding the functional value of the coating system. Recent studies have shown that multi-component systems can provide stronger preservation effects than single-polymer coatings, especially in fresh produce and minimally processed food (Santos et al., 2020). Nanochitosan is also expected to play an important role in future food preservation systems. Due to its smaller particle size and larger surface area, nanochitosan has shown improved antimicrobial performance and better coating functionality compared with conventional chitosan. In addition, nanochitosan-based systems have shown greater compatibility with controlled-release and smart preservation approaches (Iqbal et al., 2025).

Future research should also pay more attention to industrial-scale validation. More pilot-scale and commercial-scale studies are needed to evaluate coating performance under real processing, storage, transportation, and market conditions. This is especially important because many coatings that perform well in laboratory trials may behave differently under industrial handling and distribution systems (Bremenkamp et al., 2025). Economic and regulatory evaluation should also become a stronger focus in future research. Although chitosan is often described as a low-cost and sustainable material, few studies provide detailed analysis of processing cost, formulation efficiency, regulatory approval, or labeling requirements. These aspects are important because technical performance alone is not enough to support

commercial adoption, especially for nanochitosan and active composite systems (Mahmud et al., 2021). In addition, future chitosan research is expected to become more integrated with sustainable packaging technologies. The combination of chitosan coatings with biodegradable packaging, intelligent freshness sensors, and active packaging systems may offer broader opportunities for improving food quality, safety, and shelf-life monitoring in modern food systems (Usman et al., 2025).

Overall, future progress in chitosan-based edible coatings will depend on how well current research can move from promising laboratory findings toward standardized, scalable, safe, and commercially practical preservation systems.

9. Conclusion

Chitosan-based edible coatings have shown strong potential as sustainable materials for food preservation due to their biodegradability, film-forming ability, and multifunctional protective properties. Compared with many other edible coating materials, chitosan offers a broader preservative role because it can function not only as a physical barrier, but also as an active material with antimicrobial and antioxidant properties (X. Liu et al., 2023)

This review also shows that the performance of chitosan-based coatings is strongly influenced by formulation design and coating application method. Differences in molecular properties, additive incorporation, and processing techniques often lead to different preservation outcomes, even when the same base material is used (Andrade et al., 2012; Moreno et al., 2025). This explains why the effectiveness of chitosan cannot be generalized across all food systems.

Although many studies report promising results, several important limitations still remain, particularly in formulation standardization, sensory quality, coating stability, industrial scalability, economic feasibility, and regulatory validation. These challenges show that the future success of chitosan-based edible coatings will depend not only on improving preservative performance, but also on developing systems that are more consistent, practical, and commercially applicable.

Chitosan remains one of the most promising biopolymers for the development of next-generation edible coatings. With further advances in formulation design, industrial processing, and safety validation, chitosan-based coatings are expected to play an increasingly important role in sustainable food preservation and modern bioactive packaging systems.

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