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RESEARCH ARTICLE

Chitosan as a Natural Antimicrobial and Nanocarrier: Strategies for Food Preservation and Surface Protection

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Abstract

Chitosan, a naturally derived polysaccharide obtained from chitin deacetylation, has emerged as a versatile antimicrobial agent and nanocarrier with broad potential in food preservation and surface protection. Its intrinsic antimicrobial activity, biocompatibility, biodegradability, and Generally Recognized as Safe (GRAS) status make it highly suitable for sustainable food applications. The cationic nature of chitosan facilitates strong electrostatic interactions with negatively charged bacterial cell membranes, leading to cell disruption, leakage of intracellular components, and inhibition of biofilm formation. Recent advancements in nanotechnology have enhanced these properties by incorporating chitosan with metal and metal oxide nanoparticles (e.g., ZnO, Ag, TiO_2) or natural antimicrobials (e.g., essential oils, plant phenolics) to create hybrid nanocomposite coatings with synergistic effects. Such systems have demonstrated effectiveness against key foodborne pathogens like *Listeria monocytogenes*, *Salmonella Typhimurium*, and *Escherichia coli* on fresh produce, meats, and food contact surfaces. Moreover, chitosan-based films and coatings act as carriers for controlled release of antimicrobial agents, improving food shelf life while minimizing sensory and nutritional impacts. This review highlights current progress in chitosan's functional mechanisms, its integration with GRAS nanoparticles, and recent developments in food packaging and surface hygiene, emphasizing future opportunities for smart, eco-friendly antimicrobial systems in the food industry.

Keywords: Chitosan, Antimicrobial, Biofilm, Coating, Food Contact, Food Preservation, Nanocarrier.

1. Introduction

The growing global demand for safe, high-quality, and minimally processed food has intensified the need for natural antimicrobial strategies that can effectively prevent bacterial contamination and extend product shelf life without compromising nutritional or sensory attributes. Among the various biopolymers explored for food applications, chitosan, a deacetylated derivative of chitin, has received remarkable attention due to its intrinsic antimicrobial activity, film-forming capability, and biodegradability (Mawazi et al., 2024). Derived primarily from crustacean shells, fungi, or insect sources, chitosan is composed of β-(1→4)-linked D-glucosamine and N-acetyl-D-glucosamine units, which endow it with a unique cationic nature. This property enables electrostatic interactions with negatively charged microbial membranes, leading to cell lysis and inhibition of microbial growth (Aranaz et al., 2021). Beyond its direct antimicrobial effect, chitosan is classified as Generally Recognized as Safe (GRAS) by the U.S. Food and Drug Administration (FDA), making it a promising candidate for eco-friendly food preservation and food contact surface protection (FDA, 2022; El-Araby et al., 2024).

In recent years, chitosan has evolved from a simple biopolymer into a multifunctional nanocarrier system capable of encapsulating and delivering antimicrobial agents, bioactive compounds, and essential oils. This advancement addresses one of the critical challenges in food preservation, the controlled and sustained

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release of antimicrobials to maintain prolonged efficacy during storage and handling (Biswas et al., 2025). The nanoscale form of chitosan enhances its surface area, solubility, and reactivity, improving its antimicrobial performance and stability in diverse food matrices (Onyeaka et al., 2022). Furthermore, combining chitosan with other nanoparticles, such as silver (Ag), zinc oxide (ZnO), titanium dioxide (TiO_2), or silica (SiO_2), has been shown to generate synergistic effects that enhance bactericidal efficiency and broaden antimicrobial spectra (Bui et al., 2017). These chitosan-based nanocomposites function not only as barriers to microbial penetration but also as active agents capable of disrupting biofilms and preventing bacterial adhesion on food and processing surfaces.

The antimicrobial mechanism of chitosan involves multiple interactive pathways. The positively charged amino groups of chitosan interact with the negatively charged components of microbial cell membranes, leading to altered permeability, leakage of intracellular constituents, and eventual cell death (Nasaj et al., 2024). Additionally, chitosan can chelate metal ions and bind to microbial DNA, interfering with replication and transcription processes (El-Saadony et al., 2025). The molecular weight and degree of deacetylation significantly influence its antimicrobial efficiency, lower molecular weight chitosan tends to diffuse more easily through cell walls, whereas higher deacetylation enhances its cationic charge density, intensifying cell membrane interactions (Wang & Roman, 2023). These properties enable chitosan to act effectively against a broad range of microorganisms, including Gram-positive and Gram-negative bacteria, yeasts, and molds (Yan et al., 2021).

In the context of food preservation, chitosan-based coatings and films have demonstrated superior functionality in maintaining the microbial and physicochemical quality of perishable foods such as fruits, vegetables, meats, seafood, and dairy products (Ojagh et al., 2010). For example, chitosan coatings have effectively reduced microbial spoilage on strawberries and apples by forming semi-permeable barriers that regulate gas exchange and moisture loss (Rhim et al., 2013). Similarly, the incorporation of essential oils such as oregano, thyme, or cinnamon into chitosan films enhances antimicrobial efficacy while introducing antioxidant properties beneficial for lipid oxidation control (Gutiérrez et al., 2009). Beyond fresh produce, chitosan coatings have been successfully applied on food contact surfaces (stainless steel, polyethylene, polyurethane, etc.) to prevent bacterial adhesion and biofilm formation by pathogens like *Listeria monocytogenes*, *Salmonella enterica*, and *Escherichia coli* (Sapper et al., 2018; Kumar et al., 2020). Such biofilms pose persistent challenges in food processing environments, where conventional sanitizers often fail to achieve complete eradication.

Chitosan's compatibility with nanomaterials further enhances its role as an antimicrobial nanocarrier. For instance, Ag-chitosan nanocomposites exhibit strong bactericidal effects through the synergistic action of Ag^+ ion release and chitosan's membrane interaction, effectively reducing microbial load on food packaging and contact surfaces (Alavi & Nokhodchi, 2020). ZnO-chitosan films have demonstrated remarkable activity against *E. coli* and *S. aureus* while maintaining transparency and mechanical strength suitable for food packaging applications (Li et al., 2019). Moreover, TiO_2-chitosan systems have been explored for photoactivated disinfection, providing dual antimicrobial and self-cleaning functionality (Sirelkhatim et al., 2015). These hybrid nanostructures not only improve antimicrobial stability but also ensure controlled release of active agents, which prolongs their activity during storage and minimizes potential toxicity concerns.

The integration of chitosan-based nanomaterials into food systems aligns with the global transition toward sustainable and biodegradable packaging technologies. Traditional petroleum-based plastics are increasingly being replaced by biopolymer composites that reduce environmental impact while maintaining food quality and safety. Chitosan, with its renewability and functional adaptability, plays a pivotal role in this shift (Elsabee & Abdou, 2013). Furthermore, emerging studies are exploring smart chitosan coatings responsive to environmental stimuli such as pH, temperature, or microbial activity, which could provide real-time indicators of food freshness or contamination (Vimal et al., 2021).

The accumulating evidence highlights chitosan's dual function as a natural antibacterial agent and a nanocarrier platform that can incorporate GRAS nanomaterials for enhanced food preservation and hygiene applications. This study will analyze the synthesis, characterization, and functional processes of chitosan and its composites, emphasizing their uses in suppressing foodborne pathogens, preventing biofilm formation, and prolonging food shelf life. The paper will emphasize regulatory considerations, technological constraints, and future views for the implementation of chitosan-based nanocoating for sustainable food safety solutions.

2. Antimicrobial Mechanisms of Chitosan

Chitosan exhibits a unique and multifaceted antimicrobial profile that sets it apart from most natural biopolymers used in the food industry (Qu et al., 2025). Its activity stems from its cationic nature, physicochemical adaptability, and ability to form interactive complexes with microbial surfaces. The antimicrobial function is not governed by a single mechanism but rather by several simultaneous and synergistic pathways, making chitosan particularly effective against diverse foodborne pathogens such as *Listeria monocytogenes*, *Escherichia coli*, *Staphylococcus aureus*, and *Salmonella enterica*. These mechanisms operate at the membrane, metabolic, and genetic levels, ultimately arresting microbial growth or causing lethal damage. The strength of each mechanism depends on environmental conditions, including pH, ionic strength, temperature, and chitosan's intrinsic properties such as molecular weight, degree of deacetylation, viscosity, and nanoparticle configuration. Together, these factors allow chitosan to adapt to varying food environments and maintain activity across a wide range of matrices, including solid foods, liquids, packaging surfaces, and biofilms (Kong et al., 2010; Xing et al., 2017). To better visualize how chitosan disrupts microbial cells, Figure 1 illustrates its major antimicrobial mechanisms, including electrostatic interaction, membrane disruption, chelation, and DNA binding, and Table 1 summarizes how key physicochemical properties of chitosan govern its antimicrobial efficacy across different foodborne pathogens.

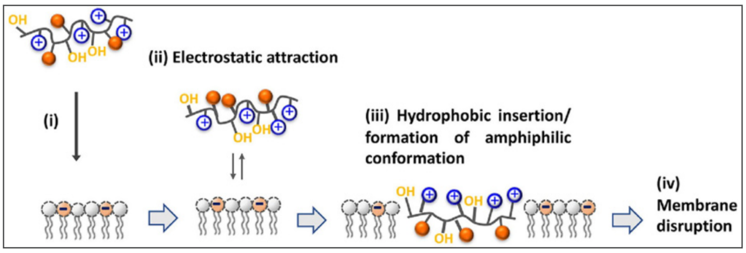

Figure 1. *Antimicrobial mechanisms of chitosan*

Table 1. *Structural factors influencing antimicrobial activity of chitosan*

Property	Description	Effect on Antimicrobial Activity
Molecular Weight	Low-MW (50–190 kDa) vs High-MW (>300 kDa)	Low-MW improves diffusion into cells; High-MW forms stronger external barriers
Degree of Deacetylation (DD)	% of free amino groups	Higher DD increases cationic charge → stronger membrane attraction
pH Sensitivity	Protonation at acidic pH	Enhanced solubility and positive charge at pH < 6.5
Solubility	Affected by MW and DD	Higher solubility improves interaction with microbial surfaces
Nanocomposite Formation	Chitosan combined with metals/EOs	Synergistic antibacterial action via ROS or ion release

2.1 Electrostatic Interaction and Membrane Disruption

Electrostatic interaction remains the most widely recognized antimicrobial pathway. Under acidic or slightly acidic conditions, chitosan amino groups become protonated, imparting a strong positive charge. This allows chitosan chains or nanoparticles to bind efficiently to negatively charged components of bacterial membranes, lipopolysaccharides in Gram-negative bacteria and teichoic acids in Gram-positive bacteria. This initial adhesion destabilizes membrane structure, increases permeability, and interferes with essential barrier functions (Liu et al., 2004; Goy et al., 2009). Studies using electron microscopy consistently show morphological alterations, including membrane wrinkling, pore formation, cytoplasmic shrinkage, and leakage of intracellular material (Helander et al., 2001). Table 2 compiles representative nanocomposite systems and their observed antimicrobial performance in food or surface protection applications.

Table 2. *Examples of chitosan-based nanoparticles and their antimicrobial behavior*

Nanocomposite	Active Mechanisms	Target Microorganisms	Food/Surface Application
Chitosan–Ag	Ag^+ ion release and membrane disruption	*L. monocytogenes*, *E. coli*	Stainless steel, packaging films
Chitosan–ZnO	ROS generation + surface binding	*S. aureus*, *E. coli*	Chicken meat, fresh produce
Chitosan–TiO_2	Photocatalytic oxidation	*E. coli*, *Pseudomonas spp.*	Food-contact surfaces

Nanocomposite	Active Mechanisms	Target Microorganisms	Food/Surface Application
Chitosan and Essential Oils	Membrane permeabilization	*Botrytis*, *Penicillium*, *Salmonella*	Strawberries, fresh-cut fruit
Chitosan–Phenolic Films	Antioxidant + antimicrobial	*Listeria*, yeasts	Surface coatings

These effects compromise osmotic balance and energy regulation, overwhelming the bacterial cell. In some cases, smaller chitosan fragments penetrate through the cell envelope and exert internal antimicrobial effects, amplifying membrane disruption through a two-step process of external damage followed by internal interference. Table 2 compiles representative nanocomposite systems and their observed antimicrobial performance in food or surface protection applications.

2.2 Chelation of Metal Ions and Enzymatic Interference

Beyond membrane destabilization, chitosan can chelate essential metal ions required for microbial growth (Kong et al., 2008). Cells rely on Mg^{2+} and Ca^{2+} for stabilizing membranes and wall structures, while Fe^{2+} serves as a cofactor in respiratory enzymes. Chitosan's chelating properties reduce the availability of these ions, inhibiting enzyme activity and destabilizing metabolic pathways (Liu et al., 2022). This process particularly affects Gram-positive bacteria, which depend on metal ions for maintaining peptidoglycan integrity (Akdaşçi et al., 2025). Additionally, chelation interferes with microbial electron transport, nutrient assimilation, and ATP production. Chitosan can also bind to extracellular microbial enzymes or toxins, reducing their virulence or rendering them inactive. This metabolic inhibition works synergistically with membrane disruption, producing both immediate and long-term effects on microbial viability (Raafat et al., 2008).

2.3 Molecular Weight, Degree of Deacetylation, and Structural Parameters

The antimicrobial efficiency of chitosan is strongly determined by its molecular architecture. Low molecular weight (LMW) chitosan exhibits superior solubility and higher penetrative ability, enabling it to enter bacterial cells and interfere with DNA and protein synthesis (Ardean et al., 2021). In contrast, high molecular weight (HMW) chitosan forms denser structural networks on bacterial surfaces, preventing nutrient transfer and creating a barrier-like suffocating effect. The degree of deacetylation (DD) plays an equally crucial role; chitosan with DD above 80–90% carries more protonated amino groups, intensifying electrostatic interactions. High-DD chitosan tends to show stronger antimicrobial effects at lower concentrations, whereas medium-DD chitosan offers balanced solubility and film-forming ability, making it suitable for coating applications (Benhabiles et al., 2012). Environmental pH greatly modulates these interactions; at lower pH, protonation increases, expanding the chitosan's functional range in acidic food systems such as fruits, beverages, and fermented products.

2.4 Synergistic Mechanisms with Nanoparticles and Bioactive Molecules

The emergence of chitosan-based nanocomposites has dramatically expanded the range of antimicrobial mechanisms. When chitosan is combined with nanoparticles such as Ag, ZnO, TiO_2, or even natural antimicrobials like essential oils and phenolics, multiple antimicrobial pathways are activated simultaneously. For example, Ag–chitosan nanocomposites combine membrane disruption from chitosan with silver-ion release, which binds to thiol-containing enzymes and mitochondrial proteins, causing respiratory collapse (Alavi & Nokhodchi, 2020). ZnO–chitosan systems produce reactive oxygen species (ROS), including superoxide radicals and hydrogen peroxide, that oxidize cell components and trigger apoptosis-like responses in bacteria (Sirelkhatim et al., 2015). TiO_2–chitosan materials exhibit photocatalytic activity capable of degrading organic residues and destroying bacterial cells on food-contact surfaces. These synergistic systems outperform pure chitosan and provide long-lasting activity, even under challenging environmental conditions such as high organic matter, fluctuating moisture, or repeated microbial exposure.

3. Applications of Chitosan in Food Preservation

Chitosan has become a highly versatile biopolymer for food preservation due to its ability to form films, coatings, hydrogels, emulsions, and nanoparticle systems. Its compatibility with a wide range of bioactive compounds and GRAS nanomaterials makes it suitable for fresh produce, meats, seafood, dairy, bakery products, and ready-to-eat foods. Chitosan also enhances sensory quality by reducing moisture loss, delaying oxidation, and maintaining firmness and color stability. As consumer demand increases for natural preservatives and reduced chemical additives, chitosan-based systems offer industry-relevant solutions that align with clean-label and sustainability trends (Elsabee & Abdou, 2013).

3.1 Edible Films and Coatings for Fruits and Vegetables

Among its most established uses, chitosan has been widely incorporated into edible coatings for fruits and vegetables. Fresh produce typically suffers from rapid spoilage due to respiration, moisture loss, and microbial growth. Chitosan forms a semi-permeable barrier to oxygen, CO_2, and moisture, slowing down respiration rates, reducing dehydration, and delaying ripening. For fruits such as strawberries, tomatoes, apples, and blueberries, chitosan coatings significantly extend storage life by reducing fungal colonization, enzymatic browning, and weight loss (Kamali et al., 2024; Dai et al., 2025). Incorporation of essential oils, such as oregano, thyme, clove, or cinnamon, into chitosan coatings further enhance antimicrobial activity. These compounds disrupt microbial membranes through hydrophobic interactions while chitosan maintains film integrity and controls release rates (Gutiérrez et al., 2009). Dos Santos et al. (2019) explored the development of biopolymer-based films combining the polysaccharide Chitosan with two essential oils (EOs), namely cinnamon (CEO) and marjoram (MEO) and found that increased EO content typically reduced transparency, altered tensile strength and elongation, and influenced water vapor permeability. Importantly, the chitosan–EO films exhibited enhanced antimicrobial efficacy compared to chitosan alone, demonstrating significant inhibition of bacterial growth while maintaining biocompatible characteristics for potential skin contact use. When applied to vegetables like bell peppers, cucumbers, and lettuce, chitosan coatings reduce spoilage bacteria and maintain crispness, making them ideal for fresh-cut produce.

3.2 Meat and Seafood Preservation

Chitosan's role in meat and seafood preservation is particularly significant due to the high perishability and susceptibility of these foods to pathogenic bacteria and oxidative rancidity. Chitosan coatings act as oxygen barriers, limiting lipid oxidation, which is a major cause of off-flavors and discoloration in meat. For example, chitosan–cinnamon essential oil films applied to trout fillets prevented the accumulation of volatile basic nitrogen (TVB-N), inhibited psychrotrophic bacteria, and preserved sensory attributes for multiple days longer than untreated controls (Ojagh et al., 2010). In chicken meat, chitosan–ZnO nanocomposites suppress *E. coli* and *S. aureus*, while also reducing thiobarbituric acid reactive substances (TBARS), a marker of lipid oxidation (Li et al., 2019). Seafood such as shrimp and salmon also benefit from chitosan coatings, which inhibit melanosis (black spot formation), reduce microbial contamination, and retain moisture and texture during refrigerated storage.

3.3 Dairy, Bakery, and Fermented Food Applications

In the dairy sector, chitosan enhances microbial stability in cheese, yogurt, and milk by inhibiting mold, yeast, and spoilage bacteria. Chitosan nanoparticles can encapsulate probiotics, improving their survival during processing, refrigerated storage, and gastrointestinal passage (Perinelli et al., 2020). This advances the development of functional dairy foods with enhanced health-promoting properties. In bakery applications, chitosan reduces fungal contamination on bread and pastries, minimizes quality degradation from moisture migration, and maintains crust texture. Chitosan's interactions with carbohydrate-protein matrices can also adjust water activity, making it a natural antifungal preservative suitable for gluten-free or low-sugar baked goods. Fermented foods benefit from chitosan's selective antimicrobial effect because it inhibits undesirable bacteria while sparing beneficial fermentative microbes.

3.4 Chitosan Nanocarriers for Controlled Release of Antimicrobials

One of the most innovative uses of chitosan is its function as a nanocarrier system for targeted and controlled release of antimicrobials, antioxidants, or nutraceuticals. Encapsulation of essential oils (e.g., thymol, carvacrol, eugenol), organic acids, phenolics, or natural extracts protects these compounds from degradation, improves solubility, and enables sustained release into food matrices (Perinelli et al., 2020). Controlled release ensures long-lasting antimicrobial action while minimizing strong aromas or flavors associated with potent natural compounds. Chitosan nanoparticles also enhance the distribution of bioactive molecules within complex foods, enabling more uniform protection across surfaces and internal structures. In high-moisture foods, chitosan hydrogels or emulsions provide moisture-retentive antimicrobial reservoirs that maintain activity for extended periods.

3.5 Smart Packaging and Responsive Chitosan-Based Systems

Recent advances have introduced chitosan into the realm of smart and active packaging technologies. Functional chitosan films can incorporate pH indicators, freshness sensors, oxygen scavengers, or gas regulators that respond to spoilage events. For example, chitosan films infused with anthocyanins change color in response to pH shifts associated with microbial growth, offering real-time freshness indicators (Vimal et al., 2021). Other systems incorporate nanoparticles that release antimicrobials in response to humidity, temperature changes, or mechanical damage. This dynamic packaging approach allows chitosan materials to not only protect food but also communicate its safety and quality to consumers.

4. Chitosan-based Coatings for Food Contact Surface Protection

Effective protection of food-contact surfaces is a critical aspect of food safety because cross-contamination from equipment surfaces is a major source of foodborne illness. Chitosan-based coatings offer an eco-friendly and durable means of reducing microbial adhesion, preventing biofilm formation, and adding antimicrobial properties to traditionally inert materials such as stainless steel, polyethylene, polyurethane, rubber, and conveyor belts. Unlike chemical sanitizers that act momentarily and rapidly lose activity, chitosan coatings provide persistent antimicrobial functionality, making them ideal for surfaces that undergo repeated contact with food or moisture.

4.1 Mechanisms of Reduced Adhesion and Biofilm Inhibition

Biofilm formation begins with bacterial adhesion to surfaces, followed by colonization and secretion of extracellular polymeric substances (EPS). Chitosan coatings interrupt this early adhesion phase through several mechanisms. First, the positive charge of chitosan repels or disrupts negatively charged bacterial cell surfaces, reducing the strength of adhesion. Second, chitosan-modified surfaces become more hydrophilic, decreasing the ability of bacteria, especially hydrophobic Gram-negative strains, to establish stable contact (Liu et al., 2025). Third, chitosan forms a thin antimicrobial film that continuously interferes with bacterial attachment, even under cycles of wetting and drying. When bacteria do manage to contact the surface, chitosan disrupts extracellular polysaccharides, preventing the formation of structured biofilms. Over time, fewer bacteria survive to proliferate, dramatically lowering the risk of persistent contamination.

4.2 Composite Nanocoatings with Nanoparticles

Combining chitosan with nanoparticles (Ag, ZnO, TiO_2, SiO_2) enhances its durability, mechanical properties, and antimicrobial strength. Silver–chitosan coatings release Ag^+ ions that penetrate bacterial cell walls, inhibit protein synthesis, and disrupt the respiratory chain, making them potent against both planktonic cells and mature biofilms (Alavi & Nokhodchi, 2020). ZnO–chitosan nanocoatings provide long-term ROS-based antimicrobial activity, which remains effective even under high humidity or organic load, conditions where many sanitizers fail (Li et al., 2019). TiO_2–chitosan coatings are photocatalytically active, degrading bacterial cells and organic residues under UV or indoor light, enabling self-cleaning functionality (Sirelkhatim et al., 2015). These composite coatings have been tested on stainless steel, plastic cutting boards, conveyor belts, and packaging equipment, consistently demonstrating strong reductions in microbial adhesion and biofilm density.

4.3 Applications in Industrial Food Processing Environments

In industrial settings, surfaces frequently contact raw materials, equipment, workers' hands, and airborne contaminants. Chitosan-based coatings offer a stable antimicrobial layer that withstands mild washing, abrasion, and temperature changes. On stainless steel, the most common food-contact surface, chitosan coatings achieve over 90% reduction in attachment by pathogens such as *Listeria monocytogenes* and *Salmonella enterica* (Kumar et al., 2020). When applied on polyurethane or polyethylene, chitosan prevents biofilm maturation and reduces cross-contamination between batches. Conveyor belts coated with chitosan–ZnO composites maintain antimicrobial activity across multiple cleaning cycles, reducing microbial harboring in joints and crevices where sanitizers often fail. Such applications offer substantial benefits for poultry plants, processing lines, dairy equipment, and ready-to-eat food facilities, where biofilm control is a major challenge.

4.4 Regulatory Considerations and Practical Challenges

Although chitosan is GRAS and widely used, adopting chitosan-based coatings at industrial scale requires adherence to regulatory frameworks established by FDA, EFSA, and other agencies. Migration limits, surface residue levels, nanoparticle safety, and environmental impacts must be evaluated. Ensuring uniform coating thickness, stability, and adhesion across different surface types remains a technical challenge. Variability in chitosan source, purity, and molecular characteristics can also affect performance. Standardizing synthesis protocols, nanoparticle concentrations, and testing procedures will be essential for commercial deployment (Perinelli et al., 2020). Nevertheless, the growing focus on sustainable antimicrobial technologies strongly supports the future integration of chitosan-based surface coatings in industrial food environments.

5. Future Prospects

Future applications of chitosan in food preservation and surface protection are poised to expand significantly as advancements in material science, nanotechnology, and sustainable processing converge. One promising direction is the development of next-generation chitosan nanostructures that exhibit precisely tunable physicochemical properties, such as surface charge, hydrophobicity, and molecular weight distribution, to optimize antimicrobial performance across different food matrices. Emerging synthesis strategies, including enzymatic modification, microfluidic-assisted nanoparticle fabrication, and green solvothermal processing, will help achieve more uniform particle sizes and improved functional stability, enabling chitosan systems to meet industrial performance standards. Another key frontier lies in smart and intelligent packaging technologies, where chitosan films incorporate real-time freshness indicators, pH-responsive sensors, and gas-triggered antimicrobial release mechanisms to actively monitor and maintain food safety. Integration with natural pigments, biosensors, or metallic nanoparticles could create multifunctional systems capable of both antimicrobial protection and spoilage detection.

Chitosan also holds promise in biofilm-resistant industrial coatings, particularly as research deepens into long-term durability under repeated washing, thermal stress, and mechanical abrasion (Teixeira-Santos et al., 2021). Future studies should aim to develop self-renewing or photocatalytically regenerative chitosan coatings that maintain efficacy over extended operational cycles in food processing environments. Furthermore, incorporating chitosan into hybrid biopolymer blends, with alginate, pectin, PLA, starch, or cellulose nanofibers, can enhance mechanical strength, thermal stability, and migration resistance while preserving biodegradability. Addressing consumer-driven sustainability trends, researchers are expected to explore agro-waste-derived chitosan sources (e.g., mushroom or insect chitin) to reduce reliance on crustacean materials and expand vegan-certified applications. Finally, future regulatory harmonization and the establishment of standardized testing frameworks for nanoparticle migration, toxicity, and environmental fate will accelerate commercialization. As interdisciplinary collaborations strengthen among food scientists, material engineers, microbiologists, and regulatory bodies, chitosan-based antimicrobial technologies are positioned to become major contributors to next-generation food safety solutions.

6. Conclusions

Chitosan stands out as one of the most versatile natural polymers for improving food preservation, enhancing food-contact surface hygiene, and advancing sustainable packaging technologies. Its intrinsic antimicrobial activity, biocompatibility, and GRAS status, paired with its ability to form films, coatings, hydrogels, emulsions, and nanoparticles, enable broad usefulness across fruits, vegetables, meats, seafood, dairy products, and industrial processing surfaces. The mechanisms driving its antimicrobial action are multifaceted, involving electrostatic interactions, membrane disruption, metal ion chelation, and interference with DNA and protein synthesis. These pathways provide robust protection against major foodborne pathogens, while their structural tunability allows fine control of solubility, reactivity, and film performance. The integration of chitosan with nanomaterials such as Ag, ZnO, and TiO_2, as well as essential oils and phenolics, has amplified its antimicrobial and antibiofilm efficacy, creating functional systems capable of long-term and environment-responsive protection.

Applications in food preservation demonstrate significant reductions in microbial spoilage, delayed oxidation, improved texture retention, and extended shelf life. On food-contact surfaces, chitosan-based coatings serve as persistent antimicrobial barriers that inhibit bacterial adhesion and biofilm formation, addressing a major challenge in industrial environments. Despite these advances, opportunities remain to enhance scalability, stability, and regulatory standardization. Continued innovation in nanostructure design, smart packaging, hybrid biopolymer systems, and sustainable sourcing will further elevate chitosan's potential. Overall, chitosan represents a powerful, eco-friendly, and adaptable platform poised to shape the future of food safety, preservation, and hygienic processing technologies.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

7. References

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