Mechanical and Barrier Properties of Chitosan-based Composite Film as Food Packaging: A Review

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Chitosan can serve as a natural alternative to petroleum-based components in food packaging; however, the mechanical and barrier properties of pure chitosan film possess certain limitations. This paper presents a comprehensive review on the mechanical and barrier properties of composite films formed by combining chitosan-based films with plasticizers, polysaccharides, proteins, and lipids. These composite films often exhibit superior mechanical strength and enhanced barrier performance compared to pure chitosan film, thereby expanding the potential applications of chitosan in food packaging. Chitosan represents an ideal raw material for developing innovative biofilms that can cater to diverse packaging requirements for various food products while offering promising prospects for broad application.

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INTRODUCTION

The primary materials utilized in traditional food packaging encompass paper, plastic, metal, and glass. Some characteristics of paper products, such as printability, favor its prominent usage in the food packaging industry as primary and secondary packaging products (Adibi *et al*. 2023). However, paper items are inherently porous and highly hydrophilic, as a result of their being formed from cellulosic fibers having various orientations. These characteristics present challenges in food packaging applications due to their inherent limitations in providing effective barriers against gases, water, and grease (Bhardwaj *et al*. 2020; Semple *et al*. 2022). Petroleum-based polymers such as polyethylene, polypropylene, polyvinyl chloride, and polystyrene are widely used due to their good mechanical properties, thermal sealing, and resistance to permeation of water vapor and oxygen, as well as their low cost. However, these polymers are not biodegradable, resulting in the accumulation of plastic waste and becoming a serious social problem (López-Palestina *et al.* 2019; Nisar *et al.* 2019; Pang *et al.* 2019). Metal and glass possess excellent barrier properties and have a longstanding history in food packaging. However, metal packaging is relatively costly and exhibits chemical instability, while glass packaging is susceptible to breakage and carries a significant weight, which may result in increased transportation costs and risks (Gallucci *et al.* 2021; Channa *et al*. 2022; Joshi *et al*. 2024). One way to solve these problems is to develop biodegradable polymers for usage in environmentally friendly food packaging. Because biodegradable polymers can prevent

water loss, aroma loss, water absorption, and oxygen penetration in food (Cazon *et al.* 2017), they can replace petroleum-based polymers to a certain extent.

Furthermore, due to their edibility, biodegradable polymers can directly come into contact with food and utilize their own properties to prolong the shelf life of food (Khanzada *et al.* 2023). Consequently, the utilization of these materials in food preservation has garnered increasing attention. The development of new biopolymers primarily relies on renewable natural resources such as proteins, lipids, polysaccharides, and their blends (Nisar *et al*. 2019; Tyagi *et al.* 2019).

Chitosan has emerged as one of the most extensively studied biodegradable polymers in recent years, owing to its safety, non-toxicity, biodegradability, biocompatibility, biofunctionality, film-forming ability, and antibacterial properties (Khan *et al.* 2012; Kumar *et al.* 2018; Cazon *et al.* 2020). As the second most available polysaccharide globally (after the cellulose and hemicellulose family) and obtainable from abundant renewable resources at a low cost (Ren *et al.* 2017; Divya and Jisha 2018; Lyu *et al*. 2021), chitosan holds great potential as an inexpensive packaging material that can reduce overall product costs while offering broad market prospects. With excellent film-forming characteristics along with selectivity and permeability towards CO_2 and O_2 gases, coupled with remarkable antibacterial properties, chitosan can be directly applied for packaging purposes, thereby enhancing both food safety and shelf life (Aguirre-Loredo *et al.* 2016; Fauzi *et al.* 2019; Vijayakumar *et al.* 2022). Several strategies have been proposed to enhance the functional properties of chitosan films and broaden their potential applications, such as modifying the degree of deacetylation, pH, solvent selection, and incorporating plasticizers or other components such as proteins or polysaccharides (Pelissari *et al.* 2009; Wang *et al.* 2015; Lopez-Mata *et al.* 2018; Liu *et al.* 2022). The aim of this work was to review the literature on mechanical and barrier properties of chitosan-based composite films.

PROPERTIES OF CHITOSAN FILM

Formation of Chitosan Film

Chitosan is an alkaline polysaccharide, which is a natural polymer formed by the random distribution of (1,4)-2-amino-2-deoxy-β-D-glucan groups along the chains. It is mainly derived from chitin, one of the most abundant biological materials in the world and primarily obtained from crustacean shells such as shrimp and crabs (Giannakas *et al.* 2014; Rohi Gal *et al.* 2023). Some microorganisms such as fungi and bacteria can also produce chitosan (Costa *et al.* 2017; Ke *et al.* 2021). Chitosan refers to different polymers with an average molecular weight ranging from 50,000 to 2 million Da and a deacetylation degree ranging between 40% and 98%.

The solubility of chitosan depends on factors such as acetyl group distribution on the backbone, molecular weight, and acid used for dissolution. In acidic solutions, a significant number of amino groups on chitosan molecules are protonated (Hubbe 2019; Lei *et al.* 2021). Therefore, slightly acidic solutions are commonly used for dissolving chitosan. However, when the concentration exceeds 2% (w/w), the solution becomes highly viscous (Van Den Broek *et al.* 2015). Thus, maintaining an acidic pH value becomes crucial while applying chitosan solutions. This limitation arises due to gel precipitation caused by neutralization of amino groups when the pH reaches or exceeds 6.2. To expand its application range within a neutral pH range (7.0 to 7.4), researchers have investigated

adding glycerol, which can act to stabilize chitosan solutions (Zhang *et al.* 2023). The most common method for dissolving chitosan film used in food packaging involves weak acids such as acetic acid. The casting method is widely employed among various techniques for the production of chitosan-based films (Khan *et al.* 2024; Rui *et al.* 2024; Zhang *et al.* 2024). The entanglement of chains during drying processes, along with intermolecular interactions such as electrostatic interactions and hydrogen bonds, contribute to forming chitosan films (Muxika *et al.* 2017). It should be noted that since chitosan is not thermoplastic and degrades before reaching its melting point, it cannot be extruded or molded into various shapes.

Characteristics of Pure Chitosan Film

The mechanical properties of chitosan film primarily encompass tensile strength and elongation at break. Research indicates that the tensile strength and elongation at break of an individual chitosan film are influenced by factors such as chitosan content, degree of deacetylation, molecular weight, solvent, temperature, and humidity test conditions. These research findings are presented in Table 1. To obtain a chitosan film, it is necessary to undergo drying procedures. Srinivasa *et al.* (2004) investigated the impact of three different drying methods – namely ambient temperature drying, oven drying, and infrared drying – on the film-forming properties. The results revealed minimal influence of the drying method on the mechanical properties of chitosan film.

Table 1. Mechanical and Barrier Properties of Pure Chitosan Films at Different Conditions

Chitosan concentration	Solvent	Chitosan properties	Tensile strength (MPa)	Elongation at break (%)	Water vapour permeability (g/m s Pa)	Oxygen permeability (cm^3 μm/m^2 day kPa)
1% (Leceta *et al.* 2013)	acetic acid (1%)	High molecular weight	61.8 (25°C, 20%RH)	4.59 (25°C, 20%RH)	8.07×10^{-13} (38°C, 90%RH)	6.65 (23°C，50%RH)
1% (Leceta *et al.* 2013)	acetic acid (1%)	Low molecular weight	55.8 (25°C, 20%RH)	4.58 (25°C, 20%RH)	8.07×10^{-13} (38°C, 90%RH)	7.70 (23°C，50%RH)
1% (Wang *et al.* 2022)	acetic acid (1%)	Deacetylation degree ≥95%	43.0 (25°C, 55%RH)	3.25 (25°C, 55%RH)	4.14×10^{-12} (25°C, 70%RH)	2.99 (23°C，50%RH)
2.5% (Bof *et al.* 2015)	acetic acid (1.25%)	Deacetylation degree 85%, Low molecular weight	~10.0 (25°C, 60%RH)	~58.0(25° C, 60%RH)	4.14×10^{-10} (5°C, 2000 Pa)	—
2.5% (Bof *et al.* 2015)	acetic acid (1.25%)	Medium molecular weight	~18.0 (25°C, 60%RH)	~85.0(25° C, 60%RH)	3.38×10^{-10} (5°C, 2000Pa)	—
2.5% (Bof *et al.* 2015)	acetic acid (1.25%)	Deacetylation degree 85%, High molecular weight	~60.0 (25°C, 60%RH)	~5.0(25°C, 60%RH)	4.55×10^{-10} (5°C, 2000Pa)	—

The barrier properties of chitosan film for food packaging are crucial in the assessment and prediction of the shelf life of packaged foods. One of the primary functions

of food packaging film is to hinder molecular transfer between food and the environment, thereby preserving food quality. By measuring these barrier properties, one can determine the permeability and transmission rates of gas molecules such as O_2, CO_2, water vapor, organic vapor, *etc*., through the membrane.

Water vapor permeability is an extensively researched property of biodegradable membranes due to its significant role in the deterioration reaction of food. Adequate water content helps maintain food freshness, thus preventing dehydration. Conversely, the study on oxygen permeability of degradable films has been relatively limited. Oxygen plays a crucial role in various degradation reactions in food, including oxidation reactions that can lead to changes in color, aroma, and taste; microbial growth; enzyme browning; and vitamin loss. Moreover, the impact of oxygen permeability on respiration in fresh fruits and vegetables is also highly significant.

Like other polysaccharide membranes, chitosan membranes are hydrophilic and consequently exhibit relatively low water vapor barrier properties, as demonstrated in Table 1. However, caution must be exercised when comparing the values reported in literature due to the fact that membrane permeability is not solely determined by chitosan's molecular weight, degree of deacetylation, and content; it also depends on various external factors such as measurement method, measurement temperature, humidity conditions, storage time, and storage conditions.

Under normal circumstances, the ideal material for food packaging should possess a low oxygen permeability. As evidenced by Table 1, chitosan film exhibits exceptional resistance to oxygen, comparable to commercially available polyvinylidene chloride film (Valenzuela *et al.* 2015). The molecular weight and solvent of chitosan can influence the oxygen permeability of its film (Ruiz *et al.* 2023).

Based on chitosan's chemical nature, as well as its solubility in slightly acidic water, it would be expected to form a hydrophilic film, but experiments have shown a large variability, usually indicating that the chitosan membrane is hydrophobic. Cunha *et al.* (2008) presented evidence suggesting that the apparent hydrophobicity was attributable to impurities. Hubbe (2019) proposed instead that the explanation can be found in a differing water-affinity of chitosan polymer fragments, depending on their orientation. This explanation is consistent with differences in the hydrophilic or hydrophobic character of different crystalline faces of cellulose (Yamane *et al.* 2006).

Characteristics of Composite Films Incorporating Chitosan and Plasticizers

Polymer blending is the most efficient approach to achieve novel materials with optimal properties. By incorporating chitosan with other components possessing distinct mechanical and barrier properties, a film exhibiting desired characteristics can be obtained. For instance, by blending chitosan with a substance to enhance ductility, the water vapor permeability of the film can be moderately enhanced. Typically, hydrophobic constituents such as lipids can be introduced into the chitosan matrix to augment composite elasticity.

The chitosan-based membrane serves as an effective carrier for various functional components. Enhancing the functionality of the chitosan-based membrane can be achieved by incorporating antibacterial agents or antioxidants derived from natural sources. The utilization of natural substances in improving the chitosan-based membrane ensures its biodegradability and edibility are maintained. Furthermore, the mechanical properties of chitosan-based films were enhanced through the addition of biodegradable plasticizers, yielding favorable outcomes.

Compared to petroleum-based synthetic plastic films, chitosan films exhibit a significant limitation in terms of their mechanical properties, particularly their poor extensibility. The incorporation of plasticizers as additives can effectively enhance the film's elongation at break, thereby facilitating its processing and application within the polymer industry. The addition of plasticizers to biopolymer membranes is a widely employed technique for improving their mechanical characteristics (Thakhiew *et al.* 2015).

The plasticizers commonly employed in chitosan-based films encompass polyols, such as glycerol, sorbitol, and polyethylene glycol, alongside sugars including glucose and sucrose, as well as lipids. Table 2 presents the tensile strength and elongation at break of the chitosan-based films subsequent to the incorporation of diverse plasticizers. It is evident that the mechanical properties of the composite film are predominantly influenced by factors including the type of plasticizer used, molecular weight of chitosan, degree of deacetylation, and test environment.

Table 2. Mechanical and Barrier Properties of Composite Films Incorporating Chitosan and Plasticizers

Plasticizers	Chitosan properties	Tensile strength (MPa)	Elongation at break (%)	Water vapour permeability (g/m s Pa)	Oxygen permeability (cm^3 μm/m^2 day kPa)
Polyvinyl alcohol (Leceta *et al.* 2013)	Mw 150 kDa	64.8-60.8 (25°C, 20%RH)	—	(1.2-1.8) × 10^{-9} (25°C, 50%RH)	—
Poly (ethylene oxide) (Leceta *et al.* 2013)	Mw 150 kDa	62-3.0 (25°C, 20%RH)	—	(7.4-10.6) × 10^{-10} (25°C, 50%RH)	—
Glycerol (Leceta *et al.* 2013)	Low molecular weight	23.9-36.9 (25°C, 20%RH)	27.2-37.7 (25°C, 20%RH)	(10.1-10.2) × 10^{-10} (38°C, 90%RH)	21.9-38.2 (23°C, 50%RH)
Glycerol (Thakhiew *et al.* 2015)	Deacetylation degree 90.2%, M_w 90 kDa	46.2-46.4 (25°C, 75%RH)	37.2-35.9 (25°C, 75%RH)	—	—
Glycerol (Souza *et al.* 2017)	High molecular weight	20.0 (25°C, 50%RH)	35.0 (25°C, 50%RH)	(8.4-8.8) × 10^{-10} (38°C, 90%RH)	20.0-37.4 (23°C, 50%RH)
Tannic acid/glycerol (Talón *et al.* 2017)	High molecular weight	—	—	—	206(25°C, 75%RH)
Pea starch/glycerol (Talón *et al.* 2017)	High molecular weight	—	—	—	158.4(25°C, 75%RH)

On the contrary, the addition of plasticizers to chitosan composite films also resulted in alterations in permeability. The inherent hydrophilicity of these plasticizers facilitated the diffusion of water vapor within the films, consequently augmenting their water vapor permeability. The research findings are presented in Table 2, wherein the values primarily depend on factors such as plasticizer type, chitosan molecular weight, degree of deacetylation, and ambient temperature and humidity.

The oxygen permeability of chitosan composite films with different plasticizers is presented in Table 2. Additionally, the oxygen permeability of the chitosan composite membrane is influenced by both the amount of plasticizer and storage time, whereby an increase in glycerol content leads to higher oxygen permeability. Moreover, as the storage time of glycerol-containing chitosan composite membrane increases, so does its oxygen permeability. This phenomenon can be attributed to a form of membrane degradation characterized by an increasing rate of permeability over time. Notably, factors such as the type of plasticizer, solvent, molecular weight, and deacetylation degree of chitosan, temperature, and humidity conditions, as well as storage time significantly impact the overall oxygen permeability.

Characteristics of Composite Films Incorporating Chitosan and Polysaccharides

The present study provides a comprehensive summary of the complexation and interaction between chitosan and various polysaccharides, including cellulose, starch, xanthan gum, guar gum, among others. Given that chitosan itself is also a polysaccharide, the interplay between different types of polysaccharides primarily relies on their specific type, structure, and intrinsic properties when combined with chitosan. Table 3 presents the mechanical properties of composite membranes composed of chitosan and diverse polysaccharides.

Table 3. Mechanical Properties of Composite Films Incorporating Chitosan and Polysaccharides

Polysaccharides	Chitosan properties	Testing conditions	Tensile strength (MPa)	Elongation at break (%)
Corn starch (Bof *et al*. 2015)	Deacetylation degree 85%, Low mol. weight	25°C, 60%RH	17.0 to 18.0	25.0
Corn starch (Bof *et al*. 2015)	Deacetylation degree 85%, Medium molecular weight	25°C, 60%RH	5.0 to 6.0	90.0
Corn starch (Bof *et al.* 2015)	Deacetylation degree 85%, High mol. weight	25°C, 60%RH	17.0 to 18.0	18.0
Cassava/potato starch (Santacruz *et al.* 2015)	Deacetylation degree 95%, M_w 149 kDa	30°C, 60%RH	8.21 to 11.68	—
Banana flour (Pitak *et al.* 2011)	Deacetylation degree 85%, M_w 65 kDa	Ambient temperature	5.2 to 14.2	1.7 to 2.6
Kudzu starch (Zhong *et al.* 2011)	Deacetylation degree 88%, M_w 420 kDa	25°C, 53%RH	13.7	56.6
Sodium alginate (Shen *et al*. 2021)	Deacetylation degree ≥90.0%	25°C, 55%RH	32. 9	11. 1
Carboxymethyl cellulose (Zheng *et al.* 2021)	Deacetylation degree≥90%	25°C, 55%RH	27.0	19.0
Agarose (Li *et al.* 2021)	Deacetylation degree 90.1%, Mw 200 kDa	25°C, 55%RH	69.1	—

Composite films of chitosan and cellulose exhibit the most significant enhancement in tensile strength among commonly used polysaccharides, as demonstrated in Table 3. Cellulose, derived from abundant biological resources such as wood, grass, and other plants

or synthesized by microorganisms, is a crucial polysaccharide. Consequently, the development of chitosan-cellulose biocomposite membranes has consistently remained a pivotal research direction.

Xu *et al*. (2005) investigated the impact of starch linear chain and branched chain architecture on the mechanical properties of chitosan-starch composite films, revealing a positive correlation between amylose content and tensile strength of the composite films. Additionally, further research and development is required to explore the potential blending of xanthan gum with chitosan for biodegradable film preparation.

Characteristics of Composite Films Incorporating Chitosan and Proteins

The composite membrane composed of chitosan and protein has emerged as a prominent research focus due to its edible characteristics. Chitosan can be blended with various proteins, such as gelatin, quinoa protein, whey protein, soy protein, *etc*. Incorporating protein into chitosan enhances the mechanical properties of the composite film by improving tensile strength while increasing elongation at break. Some relevant findings are presented in Table 4. Notably, the source of protein is identified as the primary factor influencing the mechanical properties of the composite membrane.

The incorporation of quinoa protein into a chitosan-based membrane using lactic acid as a solvent resulted in plasticization, leading to a decrease in the tensile strength and an increase in the elongation at break of the membrane. This can be attributed to the hydrogen bonding effect when chitosan and quinoa protein are combined to form a composite membrane. Various intermolecular interactions, including ionic interactions and hydrophobic interactions, exist between these macromolecules.

When citric acid was utilized as a solvent for chitosan, the tensile strength of quinoa egg exhibited similarity to that of lactic acid, albeit with a lesser increase in elongation at break. The incorporation of whey protein into the chitosan matrix also resulted in a reduction in tensile strength. However, unlike the impact observed upon addition of quinoa protein, an increase in protein content led to decreased flexibility of the membrane when whey protein was added.

Table 4. Mechanical Properties of Composite Films with Chitosan and Proteins

Proteins	Chitosan properties	Testing conditions	Tensile strength (MPa)	Elongation at break (%)
Quinoa protein (Valenzuela *et al.* 2015)	Deacetylation degree 75 to 80%	23°C, 60%RH	2.7	177.8
Cuttlefish skin gelatin (Jridi *et al.* 2014)	Deacetylation degree 88%	Ambient temperature	59.4 to 45.9	1.3 to 4.0
Brewer's spent grain (Lee *et al.* 2015)	Deacetylation degree 75%, High mol. weight	25°C, 50%RH	11.0 to 26.21	54.6 to 28.5
Gelatin (Bonilla *et al.* 2016)	Deacetylation degree 75 to 85%, Med. mol. weight	25°C, 53%RH	3.0 to 4.0	24.0
Gelatin (Dong *et al.* 2022)	Deacetylation degree ≥95%	25°C, 55%RH	71.7 to 94.2	12.3 to 20.9

Characteristics of Composite Films Incorporating Chitosan and Lipids

Blending essential oil with chitosan-based membranes can enhance their functional properties, thereby expanding their application potential. Essential oils are lipid substances

derived from plants and consist of terpenoids, phenols, aromatic compounds, and aliphatic components. These essential oils often possess antioxidant and antibacterial properties, making them commonly used in the development of active packaging solutions. Moreover, the hydrophobic nature of plant essential oils aids in reducing water vapor permeability in composite membranes (Hafsa *et al.* 2016). However, it should be noted that incorporating higher proportions of plant essential oils may result in a decrease in tensile strength but the impact on elongation at break depends on the specific properties of both the plant essential oils and chitosan (as shown in Table 5).

Using chitosan as the primary raw material, Shen and Kamdem (2015) successfully fabricated active biodegradable membranes incorporating 10% to 30% (w/w) of citronella essential oil and cypress essential oil. The tensile strength of the composite membranes exhibited a decrease with increasing essential oil content, while the variation in elongation at break was dependent on both the specific type of essential oil employed and its final concentration added. Conversely, when ginger, rosemary, sage, tea tree, and thyme essential oils were blended with a chitosan-glycerol solution, no significant disparities in mechanical properties were observed compared to control samples containing only chitosan. Additionally, other commonly utilized essential oils in chitosan-based membranes include clove essential oil and grape seed extract (Moradi *et al.* 2012; Lee *et al.* 2018).

Table 5. Mechanical Properties of Composite Films Incorporating Chitosan and Lipids

Lipids	Chitosan properties	Testing conditions	Tensile strength (MPa)	Elongation at break (%)
Citronella essential oil (Shen and Kamdem 2015)	Deacetylation degree 75%	22°C, 30%RH	33.0 to 17.1	14.5 to 8.3
Cedarwood oil (Shen and Kamdem 2015)	Deacetylation degree 75%	22°C, 30%RH	36.5 to 22.3	25.8 to 5.1
Zataria multiflora Boiss. essential oil (Moradi *et al.* 2012)	Deacetylation degree 75 to 85%, Mw 450 kDa	25°C, 52%RH	6.0	19.0
Clove essential oil (Lee *et al.* 2018)	Deacetylation degree 75%, Mw 190 to 310 kDa	25°C, 50%RH	~12.0	~22.0
Cinnamon essential oil (Rezaei *et al.* 2010)	Deacetylation degree 75 to 85%, Mw 190 to 310 kDa	25°C, 51%RH	29.2	3.6
Caraway essential oil (Hromis *et al.* 2015)	Deacetylation degree 80%	Ambient temperature	44.5 to 2.0	31.5 to 5.6
Thyme essential oil (Talón *et al.* 2017)	High molecular weight	25°C, 75%RH	13.0	39.0

CONCLUSIONS AND PROSPECTS

There is an increasing demand for the development of novel biodegradable polymers that possess not only biodegradability but also edibility, thereby ensuring food safety and minimizing both food and packaging waste while simultaneously extending the shelf life of food products. The utilization of renewable natural resources in the

development of these new biopolymers is essential to mitigate the environmental issues associated with petroleum-based polymers. Chitosan emerges as an ideal raw material for fabricating innovative biofilms, which can be blended with plasticizers, proteins, polysaccharides, and lipids to form chitosan composite films for food packaging applications. Currently, the majority of research on chitosan composite films remains confined to laboratory investigations and small-scale trials. Large-scale commercial reports on chitosan composite films are still scarce due to various factors including cost constraints. However, chitosan composite films exhibit superior mechanical properties and barrier performance, making them suitable for diverse packaging requirements across various food types. Therefore, their potential applications in the field of food packaging are extensive.

The development trend and future development of chitosan-based composite films for food packaging may be in the following aspects:

One of the primary challenges with chitosan films is their relatively poor water vapor barrier properties compared to conventional synthetic polymers. The barrier properties of chitosan films can be enhanced by incorporating nano-fillers such as clay, graphene oxide, and metal nanoparticles. These composite materials exhibit a remarkable reduction in gas and water vapor permeability, rendering them highly suitable for food packaging applications.

The inherent antimicrobial properties of chitosan can be further augmented by incorporating natural antimicrobials, such as essential oils, organic acids, or enzymes, into the film matrix. This strategy effectively extends the shelf life of packaged foods by inhibiting the growth of spoilage and pathogenic microorganisms.

By incorporating active agents such as antioxidants or nutraceuticals into chitosan films, the development of active packaging systems capable of interacting with food and prolonging its shelf life or providing additional health benefits becomes feasible.

The adherence of chitosan-based composite films to regulatory standards for food contact materials is imperative in order to facilitate their widespread adoption within the food packaging industry.

Reaching a larger scale of production for chitosan films and optimizing their cost is imperative to ensure their commercial viability and facilitate widespread adoption in food packaging.

In conclusion, the development of chitosan-based composite films for food packaging is a rapidly evolving field, with numerous opportunities for innovation and improvement. By addressing the challenges mentioned above and leveraging the unique properties of chitosan, it is possible to create sustainable, functional, and effective food packaging solutions for the future.

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