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# Review on Enhancing the Physicomechanical Properties of Chitosan and Konjac Glucomannan Edible Films with Pickering Emulsions Containing Essential Oils for Sustainable Food Packaging

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## ABSTRACT

Pickering emulsion-based edible films are gaining attention as sustainable food packaging materials due to their ability to improve mechanical strength and moisture resistance. Chitosan (CS) and konjac glucomannan (KGM) are widely used biopolymers in edible films, but chitosan films are brittle, while KGM films have poor mechanical strength and high moisture sensitivity. Incorporating Pickering emulsions (PEs) containing essential oils into CS and KGM films can significantly enhance flexibility, tensile strength, and water vapor resistance, making them more effective for food preservation. This review explores the physicomechanical properties of CS and KGM films containing Pickering emulsions, focusing on tensile strength, elongation at break, water vapor permeability, and moisture retention. The findings indicate that solid stabilizing particles in PEs reinforce the polymer network, increasing tensile strength, while essential oils improve flexibility but may reduce strength at higher concentrations. Additionally, the hydrophobic nature of essential oils and the physical barrier effect of PEs reduce water absorption and solubility, enhancing the film's durability in humid environments. Despite growing research, there is currently no comprehensive review that systematically examines how Pickering emulsions affect the mechanical and moisture barrier properties of CS and KGM films, highlighting a significant knowledge gap. Therefore, this review is essential to consolidate existing findings, clarify the mechanisms involved, and provide guidance for optimizing edible film formulations for improved food packaging applications.

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## INTRODUCTION

In recent years, the development of biodegradable edible films has received considerable attention due to growing concerns about environmental pollution caused by synthetic plastic packaging. The food industry, in particular, has shown a strong interest in biopolymeric films as sustainable alternatives to conventional plastic materials. Among various biopolymers, chitosan and konjac glucomannan have emerged as promising candidates due to their excellent film-forming abilities, biodegradability, and biocompatibility. Chitosan, a linear polysaccharide derived from chitin, possesses unique antimicrobial properties, high mechanical strength, and good film transparency, making it highly suitable for food packaging applications. However, its intrinsic brittleness and high water sensitivity limit its practical applications (Mirzaee Moghaddam & Rajaie, 2021). On the other hand, konjac glucomannan, a neutral hydrophilic polysaccharide extracted from the tubers of Amorphophallus konjac, is known for its ability to form strong hydrogen bonds, improve film flexibility, and enhance water-holding capacity. Despite these advantages, konjac glucomannan alone exhibits poor mechanical strength and high moisture absorption, which can compromise the overall performance of edible films (Qiao et al., 2025). Pickering emulsions are emulsions stabilized by solid particles rather than surfactants. These solid particles, often in the form of biopolymers, proteins, or nanoparticles, adsorb at the oil-water interface and create a stable emulsion system (Ribeiro et al., 2021). The use of Pickering emulsions in edible films has been extensively studied due to their ability to enhance mechanical strength, improve barrier properties, and enable the controlled release of bioactive compounds. In the context of food packaging, the incorporation of essential oils into Pickering emulsions offers additional advantages (Cheng et al., 2024). Essential oils are well-known for their strong antimicrobial and antioxidant properties, which can extend the shelf life of perishable food products (Basavegowda & Baek, 2021). However, their direct incorporation into biopolymer films is often challenging due to their high volatility, poor water solubility, and susceptibility to oxidation (Basumatary et al., 2022). Pickering emulsions provide an effective solution to these challenges by encapsulating essential oils, thereby enhancing their stability, controlled release, and homogeneous dispersion within the film matrix (Zhao et al., 2024). The application of Pickering emulsions in chitosan and konjac glucomannan films has the potential to significantly enhance their physicomechanical properties (Wang et al., 2024). By reinforcing the film network with emulsion droplets, Pickering emulsions can modify the microstructure of the film, reducing its porosity and increasing its density (Zhang et al., 2024). This, in turn, can lead to an improvement in mechanical properties, such as tensile strength and flexibility, while simultaneously reducing water vapor permeability and oxygen transmission rates (Wang et al., 2020). Additionally, the inclusion of solid-stabilized emulsions can prevent phase separation within the biopolymeric matrix, ensuring a more uniform distribution of essential oils and other functional additives (Dupont et al., 2021). As a result, chitosan-konjac glucomannan films incorporating Pickering emulsions exhibit improved durability, enhanced functional performance, and better suitability for food packaging applications. The primary objective of this review is to comprehensively examine the impact of Pickering emulsions containing essential oils on the physicomechanical properties of chitosan and konjac glucomannan edible films. The review aims to explore how the incorporation of Pickering emulsions influences key mechanical parameters such as tensile strength, elongation at break, and Young's modulus, as well as barrier properties such as water vapor permeability and moisture.

Despite the availability of some review articles related to edible films and Pickering emulsions, these studies often focus separately on either the biopolymer characteristics or the general applications of Pickering emulsions, without fully addressing their combined effects in chitosan and konjac glucomannan films. Many existing reviews lack a detailed analysis of the synergistic impact of Pickering emulsions containing essential oils on the mechanical and barrier properties of these films. Additionally, there is insufficient discussion on optimizing the emulsion composition and concentration to achieve a proper balance between flexibility, strength, and moisture resistance. This knowledge gap limits the practical application of these composite films in food packaging. Therefore, this review integrates and synthesizes recent research findings to provide a comprehensive understanding of how Pickering emulsions improve the physicomechanical properties of chitosan and konjac glucomannan films. By thoroughly examining the interactions among emulsion particles, essential oils, and the film matrix, it offers valuable guidance for future studies and the development of more sustainable and effective food packaging materials.

To provide a clear and structured overview, this review is organized into several key sections. First, the physicomechanical properties of chitosan and konjac glucomannan-based films are discussed, with a focus on their inherent mechanical and barrier limitations. The following sections explore the role of Pickering emulsions, particularly those containing essential oils, in modifying these properties. The mechanisms of stabilization, interactions between Pickering emulsion droplets and the biopolymer matrices, and their effects on essential oil retention, mechanical reinforcement, and barrier performance are thoroughly analyzed. Finally, the review addresses current challenges and outlines future research directions, including formulation optimization and industrial scalability for sustainable food packaging applications.

## Physicomechanical Properties of Chitosan and Konjac Glucomannan Films

### Mechanical Properties

The mechanical properties of edible films determine their practical application in food packaging, influencing their durability, handling, and protective ability (Mirzaee Moghaddam et al., 2014). Chitosan and konjac glucomannan, as two distinct biopolymers, exhibit different mechanical characteristics, each with specific advantages and limitations. Understanding their individual mechanical behaviors is essential for optimizing their use in film-forming applications.

### Chitosan-Based Films

Chitosan is known for its relatively high tensile strength (TS) due to its semi-crystalline nature and strong intermolecular hydrogen bonding. The rigid backbone structure of chitosan, which consists of β-(1→4)-linked D-glucosamine and N-acetyl-D-glucosamine units, contributes to its mechanical robustness. The degree of deacetylation plays a critical role in determining tensile properties, as a higher deacetylation degree leads to stronger hydrogen bonding, resulting in increased film strength. However, despite its high tensile strength, chitosan films are inherently brittle and exhibit low elongation at break (EB), meaning they lack flexibility and tend to crack under mechanical stress (Maluin, 2024). The Young's modulus (YM) of chitosan-based films is generally high, indicating a rigid and less deformable material (El Kadib et al., 2023). The stiffness of chitosan films makes them suitable for applications requiring structural integrity, but their brittleness can be a significant drawback. To improve the flexibility of chitosan films, various approaches have been explored, including the addition of plasticizers such as glycerol or sorbitol. Plasticizers disrupt intermolecular interactions and introduce free volume within the polymer matrix, increasing elongation at break. Another strategy involves crosslinking with agents such as genipin, citric acid, or sodium tripolyphosphate, which enhances film cohesion and modifies mechanical properties (Nikbakht et al., 2024). Additionally, blending chitosan with other biopolymers or reinforcing agents such as nanocellulose or protein-based nanoparticles can lead to improved mechanical flexibility while maintaining adequate tensile strength.

### Konjac Glucomannan-Based Films

Konjac glucomannan (KGM) films exhibit a very different mechanical behavior compared to chitosan. Unlike chitosan, KGM is an amorphous, highly hydrophilic polysaccharide, which results in films with low tensile strength but high elongation at break (Cheng et al., 2002). The flexibility of KGM films is attributed to the random coil conformation of glucomannan chains, which allows for greater molecular mobility and deformation under stress (Ye et al., 2021). As a result, KGM films are significantly more stretchable than chitosan films, making them suitable for applications requiring flexibility. However, the low tensile strength of KGM films means that they lack mechanical rigidity and are prone to tearing or deformation under excessive force. The Young's modulus of konjac glucomannan films is relatively low, reflecting their soft and pliable nature (Santos et al., 2020). To enhance the mechanical strength of KGM films, several strategies have been explored, including heat-induced gelation, which promotes intermolecular crosslinking and improves structural integrity (Wang et al., 2023). Additionally, reinforcing agents such as cellulose nanofibers, protein-based fillers, and polyphenolic compounds have been used to strengthen the film network while preserving flexibility. Another common approach is the use of ionic crosslinkers such as calcium ions, which interact with hydroxyl and acetyl groups in the KGM matrix to form a more cohesive structure with improved mechanical properties (Li et al., 2018).

### Barrier Properties

Barrier properties are critical in determining the ability of edible films to protect food products from external factors such as moisture and oxygen. The water vapor permeability (WVP) and moisture absorption capacity of a film influence its effectiveness in preserving food freshness and extending shelf life. Chitosan and konjac glucomannan exhibit distinct barrier properties due to their structural differences, requiring specific strategies to optimize their performance in food packaging applications.

### Water Vapor Permeability (WVP) and Moisture Absorption

Chitosan films generally have low water vapor permeability due to their dense molecular structure and strong hydrogen bonding network, which restricts the diffusion of water molecules (Benbettaïeb et al., 2014). The hydrophobic nature of the acetyl groups present in partially deacetylated chitosan further contributes to its moisture resistance (Franca et al., 2011). However, chitosan's ability to absorb moisture from the environment depends on its degree of deacetylation and molecular weight (Carrera et al., 2023). Highly deacetylated chitosan tends to be more hydrophilic, leading to greater water uptake, which can compromise the film's integrity over time. Its relatively good moisture barrier properties, chitosan films are often modified to further reduce WVP, especially in high-humidity environments (Mohammed et al., 2024). Strategies such as lipid coatings, incorporation of hydrophobic nanoparticles, or blending with water-insoluble polymers have been employed to improve chitosan's resistance to moisture (Nazari et al., 2025). Additionally, incorporating hydrophobic Pickering emulsions can further reduce WVP by forming a discontinuous water-repelling phase within the film matrix. konjac glucomannan films exhibit high water vapor permeability due to their extreme hydrophilicity (Zhang & Rhim, 2022). The abundance of hydroxyl groups in KGM molecules leads to strong water-binding capacity, making KGM-based films highly sensitive to humidity (Momtaz & Chen, 2020). This characteristic is beneficial in applications requiring moisture retention, such as in hydrogel-based wound dressings, but it presents a challenge for food packaging, where moisture resistance is critical. To counteract the high WVP of KGM films, various modification techniques have been investigated. Crosslinking with polyphenols, ionic interactions with multivalent cations (e.g., $Ca^{2+}$), and the inclusion of hydrophobic agents such as beeswax or fatty acids have been shown to improve the moisture barrier properties of KGM films. Additionally, structuring KGM films with Pickering emulsions stabilized by nanoparticles can introduce hydrophobic domains, reducing water diffusion while maintaining flexibility (Li et al., 2024).

## Pickering Emulsions and Their Role in Modifying Film Properties

The incorporation of Pickering emulsions into biopolymeric films has emerged as an effective strategy for improving both mechanical and barrier properties while simultaneously enhancing the functionality of the films. Pickering emulsions, which are stabilized by solid particles rather than traditional surfactants, offer a unique advantage in edible film applications, particularly in preventing essential oil volatilization, improving emulsion stability, and reinforcing the polymer matrix. When incorporated into chitosan (CS) and konjac glucomannan (KGM) films, Pickering emulsions interact differently with each biopolymer due to their distinct structural and physicochemical properties. This section explores the stabilization mechanism of Pickering emulsions and their effects on the mechanical and barrier properties of CS and KGM films, highlighting their role in enhancing the performance of biodegradable food packaging materials.

### Mechanism of Pickering Emulsion Stabilization

### Stabilization of Essential Oils via Solid Particles

Essential oils (EOs) are widely used in food packaging due to their antimicrobial and antioxidant properties, but their incorporation into edible films presents challenges related to volatility, oxidation, and poor dispersion in hydrophilic polymer matrices. Pickering emulsions provide a stable encapsulation system, where solid particles adsorb at the oil-water interface, forming a rigid interfacial layer that prevents droplet coalescence and phase separation (Yang et al., 2017). The type of stabilizing particles used such as polysaccharides, proteins, or nanoparticles influences the stability and dispersion of essential oils within CS and KGM films. Figure 1 shows the chitosan and konjac glucomannan film containing Pickering emulsion.

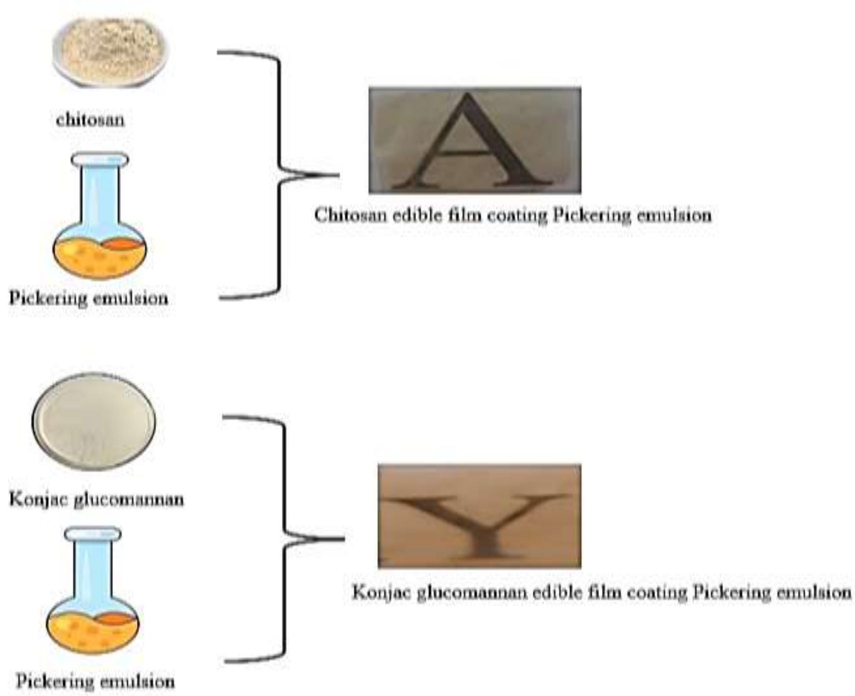


**Figure 1.** Chitosan and konjac glucomannan film containing Pickering emulsion

### Interaction between PE Droplets and Chitosan Film Matrix

Chitosan-based films are characterized by a semi-crystalline structure and strong intermolecular hydrogen bonding, which results in high tensile strength but poor flexibility (Thambiliyagodage et al., 2023). When Pickering emulsions are incorporated into chitosan films, the interaction between the positively charged chitosan chains and negatively charged or neutral stabilizing particles determines the extent of emulsion integration (Hosseini et al., 2020). The presence of solid-stabilized EO droplets within the chitosan matrix alters its microstructure, introducing discontinuities that reduce brittleness and enhance film flexibility. Moreover, the encapsulation of essential oils prevents their direct contact with the polymer chains, reducing phase separation and improving their controlled release over time.

### Interaction between PE Droplets and Konjac Glucomannan Film Matrix

Konjac glucomannan films, in contrast to chitosan films, are highly hydrophilic, amorphous, and flexible, but they lack mechanical strength and exhibit high water vapor permeability. The incorporation of Pickering emulsions into KGM films influences their structural properties differently than in chitosan films (Zhang & Rhim, 2022). Since KGM lacks intrinsic electrostatic interactions, the stabilizing particles in the PE droplets interact mainly through hydrogen bonding and Van der Waals forces (Zhou et al., 2024). The presence of Pickering emulsions in the KGM matrix enhances film density and compactness, thereby improving mechanical reinforcement. Additionally, the solid-stabilized oil droplets introduce hydrophobic domains, reducing the high moisture sensitivity of KGM films.

### Prevention of Essential Oil Volatilization and Migration

One of the key advantages of using Pickering emulsions in edible films is the ability to control the release and retention of essential oils (Atarian et al., 2019). In traditional emulsions, essential oils tend to migrate to the film surface, leading to rapid volatilization and decreased functional effectiveness. However, in Pickering emulsions, the solid-stabilized oil droplets remain embedded within the polymer network, providing a slow and sustained release of bioactive compounds (Mohsenabadi et al., 2018). This effect is beneficial for both chitosan and konjac glucomannan films, as it ensures prolonged antimicrobial and antioxidant activity, enhancing the functional lifespan of the films.

### Effects on Mechanical Properties

### Reinforcement of the Polymer Matrix in Chitosan Films

The incorporation of Pickering emulsions significantly influences the mechanical properties of chitosan films (Xu et al., 2020). Since chitosan films are inherently brittle and rigid, the presence of solid-stabilized oil droplets reduces internal stress concentrations by disrupting the ordered polymer structure. This modification leads to:

- A decrease in film brittleness and cracking, enhancing the flexibility of chitosan films.
- An increase in elongation at break (EB), allowing films to stretch more before breaking.
- A slight trade-off in tensile strength, as the introduction of emulsified oil droplets weakens some of the hydrogen bonds within the polymer matrix.

The nature of the stabilizing particles used in the emulsion also affects mechanical properties. Polysaccharide-based stabilizers, such as cellulose nanocrystals, provide additional reinforcement to the chitosan network, enhancing tensile properties. Protein-based stabilizers, such as whey or soy proteins, can increase film elasticity by forming flexible interfacial layers around oil droplets (Zhao et al., 2021).

### Reinforcement of the Polymer Matrix in Konjac Glucomannan Films

Unlike chitosan, konjac glucomannan films are highly flexible but mechanically weak. The addition of Pickering emulsions improves tensile strength by reinforcing the amorphous polymer matrix with solid particles, leading to:

- Stronger intermolecular interactions, which compensate for the weak mechanical strength of pure KGM films.
- Improved Young's modulus (YM), making the films more structurally stable while maintaining flexibility.
- Better film integrity, preventing excessive softening or tearing under mechanical stress.

The presence of Pickering emulsions introduces an optimal balance between strength and elasticity, making KGM films more suitable for food packaging applications requiring mechanical durability (Zhang et al., 2024). Table 1 shows the application of Pickering emulsion containing essential oil on the mechanical properties of chitosan and konjac glucomannan.

**Table 1.** Application of Pickering emulsion containing essential oil in mechanical properties of chitosan and konjac glucomannan

| Biodegradable film | Essential oil | Pickering particle | Application | Food Product Analyzed | References |
|---|---|---|---|---|---|
| **Chitosan** | Cinnamon | Zein nanoparticles | Increase of mechanical properties | – | (Fan et al., 2023) |
| **Chitosan** | Cinnamon | Cellulose nanocrystal | Reduces its mechanical strength | Pork meat | (Chen et al., 2022) |
| **Konjac glucomannan** | Oregano | Zein–pectin nanoparticle | Improve the elongation at break | – | (Zhang et al., 2022) |
| **Chitosan** | Lemon myrtle | Alkali lignin | Reduce mechanical stress | – | (Liu et al., 2022) |
| **Konjac glucomannan and Pullulan** | Tea tree | Cellulose nanofibrils | Increasing the mechanical properties of films | – | (Bu, Huang, et al., 2022) |
| **Konjac glucomannan** | Corn germ oil-oregano essential oil | Zein-pectin nanoparticle | Increase tensile strength | – | 2023(Du et al., 2023) |
| **Chitosan** | Clove | Zein and sodium caseinate | Improve tensile strength and break elongation | – | (Hua et al., 2021) |
| **Konjac glucomannan** | Oregano | Chitin nanocrystal | Reduced the mechanical properties of the films | – | (Xu et al., 2023) |

The incorporation of Pickering emulsions (PEs) containing essential oils (EOs) into biopolymeric edible films has a significant impact on their mechanical properties, particularly in terms of tensile strength, elongation at break, and structural integrity. Chitosan (CS) and konjac glucomannan (KGM) are widely used biopolymers for biodegradable film applications, but each has distinct mechanical limitations. Chitosan-based films are strong but brittle, making them prone to cracking under mechanical stress, while konjac glucomannan films are highly flexible but weak, limiting their ability to withstand mechanical forces. The integration of Pickering emulsions modifies the internal polymer structure, improving flexibility in chitosan films and reinforcing mechanical strength in konjac glucomannan films.

**Effects on Barrier Properties**

**Reduction in Water Vapor Permeability (WVP) and Oxygen Permeability (OP) in Chitosan Films**

Chitosan films exhibit moderate water vapor permeability (WVP) and excellent oxygen barrier properties due to their dense hydrogen-bonded structure (Pires et al., 2021). The incorporation of Pickering emulsions further enhances the moisture resistance of chitosan films by introducing hydrophobic oil droplets, which:

- Reduce water diffusion pathways, decreasing overall WVP.
- Improve resistance to environmental humidity, preventing film softening over time.
- Lower oxygen permeability, ensuring better protection against lipid oxidation.

The impact of emulsion droplet size and distribution is also critical in barrier performance. Smaller, well-dispersed droplets create a more uniform barrier, while larger droplets can introduce structural weak points that reduce effectiveness.

**Reduction in Water Vapor Permeability (WVP) in Konjac Glucomannan Films**

Konjac glucomannan films have high water vapor permeability, which limits their effectiveness in preventing moisture transfer (Zhang & Rhim, 2022). The incorporation of Pickering emulsions reduces WVP by introducing hydrophobic regions into the polymer matrix. This leads to:

- Improved water resistance, reducing swelling and deformation.
- Better structural integrity, preventing excessive moisture absorption.
- Enhanced oxygen barrier properties, which help extend food shelf life.

By adjusting the droplet size and stabilizing particle concentration, the barrier properties of KGM films can be fine-tuned for optimal performance in food packaging applications. Table 2 shows the application of Pickering emulsion containing essential oil on the moisture, solubility and water vapor permeability of chitosan and konjac glucomannan.

The incorporation of Pickering emulsions (PEs) containing essential oils (EOs) into biopolymeric edible films significantly alters their physical properties, affecting their mechanical strength, flexibility, density, and barrier performance. Chitosan (CS) and konjac glucomannan (KGM) are two commonly used biopolymers in food packaging, but each presents distinct physical limitations. Chitosan films tend to be brittle and rigid, while konjac glucomannan films are soft and mechanically weak. The inclusion of Pickering emulsions modifies these properties by introducing structural reinforcements and hydrophobic domains within the polymer matrix, leading to improved film integrity and functionality.

**Future Challenges and Research Directions**

Despite the promising potential of Pickering emulsions (PEs) in enhancing the physicomechanical properties of edible films, several challenges remain before their widespread industrial application in food packaging. These challenges include the optimization of PE composition for film reinforcement, ensuring cost-effectiveness, and addressing scalability issues in large-scale production. The incorporation of Pickering emulsions in chitosan (CS) and konjac glucomannan (KGM) films requires a tailored approach, as these biopolymers exhibit distinct physicochemical characteristics and interactions with emulsion-stabilizing particles. This section discusses the key challenges and future research directions related to the use of Pickering emulsions in CS and KGM films, focusing on their composition optimization for improved mechanical performance and the feasibility of their industrial-scale production for sustainable food packaging applications.

**Table 2.** Application of Pickering emulsion containing essential oil in moisture, Solubility and water vapor permeability of chitosan and konjac glucomannan

| Biodegradable film | Essential oil | Pickering particle | Application | Food Product Analyzed | References |
|---|---|---|---|---|---|
| **Chitosan / gelatin** | Cinnamon | Zein nanoparticles | Reducing water vapor permeability | – | (Fan et al., 2023) |
| **Chitosan** | Cinnamon | Cellulose nanocrystal | Increasing film resistance to water | Pork meat | (Chen et al., 2022) |
| **Konjac glucomannan** | Oregano | Zein–pectin nanoparticle | Reducing water vapor permeability | – | (Zhang et al., 2022) |
| **Chitosan** | Lemon myrtle | Alkali lignin | Reducing to moisture | – | (Liu et al., 2022) |
| **Anthocyanidin/chitosan** | Cinnamon-perilla | Collagen | Reducing water vapor permeability, improved hydrophobicity | Chilled fish fillet | (Zhao et al., 2022) |
| **Konjac glucomannan and Pullulan** | Tea tree | Cellulose nanofibrils | Increase water resistance | – | (Bu, Huang, et al., 2022) |
| **Konjac glucomannan** | Corn germ oil-oregano essential oil | Zein-pectin nanoparticle | Water reduce | – | (Du et al., 2023) |
| **Chitosan** | Clove | Zein and sodium caseinate | Decreased the water vapor permeability | – | (Hua et al., 2021) |
| **Konjac glucomannan** | Oregano | Chitin nanocrystal | Water vapor permeability firstly reduced and then increased | – | (Xu et al., 2023) |
| **Chitosan** | Grapefruit | Amphiphilic octenyl succinic anhydride konjac glucomannan | Increased water resistance and water vapor permeability | – | (Bu, Sun, et al., 2022) |

### Optimizing PE Composition for Film Strength

One of the most critical aspects in designing Pickering emulsions for edible films is the selection of appropriate stabilizing particles, as they play a crucial role in determining the mechanical properties of the final film. The choice of stabilizers must balance film reinforcement, film flexibility, and emulsion stability while ensuring food safety and biocompatibility. Additionally, the type and concentration of essential oils (EOs) encapsulated within the emulsions must be carefully optimized to achieve enhanced film performance without compromising structural integrity.

### Optimization for Chitosan-Based Films

Chitosan films are characterized by their high tensile strength but low elongation at break, which makes them brittle and prone to cracking.

The incorporation of Pickering emulsions can alter the polymer matrix, improving flexibility while maintaining mechanical integrity. However, achieving this balance requires careful selection of stabilizing particles and adjustment of EO concentration.

Nanoparticles such as cellulose nanocrystals (CNCs), chitin nanofibers, and starch-based nanoparticles have been investigated for their ability to reinforce chitosan films while maintaining their biodegradability. These particles form a dense interfacial network around oil droplets, enhancing the stability of the emulsion and preventing phase separation. Additionally, proteins such as whey protein isolate and soy protein have been explored as natural stabilizers, contributing to both emulsion stability and film flexibility. Future research should focus on comparing the effectiveness of different stabilizers in improving the physicomechanical properties of chitosan films. The type of essential oil incorporated within the Pickering emulsion affects both the structural properties of the film and its functional performance. Essential oils with high hydrophobicity and low volatility (thyme, oregano, or rosemary oil) tend to provide better reinforcement, as they integrate more effectively within the chitosan matrix. However, an excessive concentration of EOs can lead to phase separation and structural defects, reducing film homogeneity. Future research should explore the optimal EO-to-chitosan ratio, ensuring that essential oils improve film flexibility without compromising its tensile strength.

**Optimization for Konjac Glucomannan-Based Films**

Unlike chitosan, konjac glucomannan films exhibit high flexibility but low mechanical strength, making them prone to tearing and deformation under stress. The incorporation of Pickering emulsions can reinforce the film structure and reduce its inherent fragility. However, because KGM is highly hydrophilic, the interaction between emulsified droplets and the polymer network is different from that observed in chitosan films. In KGM-based films, the stabilizing particles must reinforce the film network while maintaining its stretchability. Polysaccharides such as pectin, alginate, and gum arabic have shown promise as natural stabilizers that interact well with konjac glucomannan molecules, forming strong hydrogen-bonded networks that improve film integrity. Additionally, inorganic nanoparticles such as silica or clay particles could be investigated as reinforcing agents to enhance mechanical strength while reducing water sensitivity. Future studies should compare the synergistic effects of different stabilizers on the structural performance of KGM films. Given that konjac glucomannan films are more hydrophilic than chitosan films, the selection of essential oils must prioritize emulsification efficiency and water compatibility. Essential oils with medium polarity (e.g., lemon oil, eucalyptus oil) may integrate more effectively within the KGM matrix, forming a uniform dispersion that reinforces the polymer network. The concentration of EOs should be carefully optimized, as excessive oil loading can increase phase separation and reduce film consistency. Further research is needed to explore the effect of EO encapsulation on water resistance and film durability in high-humidity environments.

**Industrial Feasibility**

Although extensive research has demonstrated the effectiveness of Pickering emulsions in modifying edible films, scaling up their production for commercial food packaging applications remains a significant challenge. Industrial feasibility depends on factors such as process efficiency, material cost, regulatory compliance, and environmental impact. While Pickering emulsions exhibit high stability in laboratory settings, maintaining emulsion integrity during large-scale film casting remains challenging. Variations in shear forces, drying conditions, and mixing uniformity can lead to emulsion destabilization, resulting in heterogeneous film properties. Future research should focus on developing continuous emulsification techniques that allow for uniform dispersion of PEs within the chitosan matrix. The cost of chitosan extraction and purification remains a major hurdle in commercial applications. Additionally, food safety regulations must be considered when selecting stabilizing particles, as some inorganic nanoparticles may not be permitted for direct food contact applications. Future studies should explore cost-effective natural stabilizers and assess their regulatory approval for food packaging applications.

### Challenges in Scaling Up Konjac Glucomannan-Based Films with Pickering Emulsions

For konjac glucomannan films, large-scale production is challenged by film drying efficiency, moisture sensitivity, and compatibility with industrial packaging systems. KGM films absorb moisture easily, which can lead to poor handling and reduced mechanical strength during industrial processing. The incorporation of Pickering emulsions must be optimized to create a moisture-resistant barrier while maintaining the film's natural flexibility. Research should focus on coating technologies that improve KGM film durability while maintaining its biodegradability. While konjac glucomannan is commercially available, its high cost and supply chain limitations pose challenges for large-scale applications. Developing hybrid film formulations incorporating other low-cost polysaccharides (such as starch or alginate) could enhance the cost-effectiveness of KGM-based edible films. Additionally, investigating waste-derived stabilizers (e.g., lignin, citrus fiber) could provide sustainable solutions to reduce production costs.

## CONCLUSION

The incorporation of Pickering emulsions into biopolymeric edible films has emerged as an innovative strategy to enhance their physicomechanical properties, addressing the inherent limitations of conventional biopolymer-based packaging materials. By stabilizing emulsions with solid particles, it is possible to effectively encapsulate essential oils and other functional additives, leading to improvements in mechanical strength, flexibility, and barrier performance. This approach is particularly beneficial for biopolymers such as chitosan and konjac glucomannan, each of which presents distinct challenges in film formation. While chitosan-based films exhibit high tensile strength but suffer from brittleness, konjac glucomannan films offer excellent flexibility but lack sufficient mechanical robustness. The introduction of Pickering emulsions into these matrices modifies their structural properties, creating films that are more durable, stretchable, and moisture-resistant, thus expanding their potential applications in food packaging. In chitosan-based films, Pickering emulsions function by disrupting the dense polymer network, reducing internal stresses and enhancing film flexibility. The presence of solid-stabilized oil droplets prevents excessive hydrogen bonding, leading to a reduction in film brittleness and an increase in elongation at break. Moreover, these emulsions help reduce water vapor permeability (WVP) by introducing hydrophobic domains within the polymer matrix, making the films more resistant to moisture absorption and degradation over time. Additionally, the controlled release of essential oils from the emulsion droplets provides prolonged antimicrobial and antioxidant activity, further enhancing the functional properties of chitosan films for food preservation applications.

In konjac glucomannan-based films, the role of Pickering emulsions is primarily to reinforce the film structure and improve mechanical integrity. Since KGM films are inherently soft and lack structural cohesion, the incorporation of solid-stabilized emulsions introduces a denser and more compact film network, increasing tensile strength without compromising flexibility. The hydrophobic nature of the emulsified oil phase also enhances the moisture resistance of KGM films, reducing their tendency to absorb water and swell under humid conditions. This structural modification not only improves the film's durability but also extends its applicability in packaging perishable food items that require moisture-resistant barriers. These advancements, several challenges and research gaps must be addressed to fully optimize the use of Pickering emulsions in edible film formulations. One critical area of future research involves identifying the most effective stabilizing particles that can provide both mechanical reinforcement and emulsion stability without compromising the biodegradability and edibility of the films. Natural polysaccharide-based stabilizers, such as cellulose nanocrystals, starch nanoparticles, and protein-based biopolymers, have shown great promise, but further investigations are needed to determine their long-term compatibility and scalability for industrial applications. Additionally, the selection of essential oils and their concentration within the emulsion system must be carefully optimized to achieve the desired balance between film flexibility, mechanical strength, and antimicrobial efficiency. Another major challenge involves scaling up the production of Pickering emulsion-based edible films while ensuring their cost-effectiveness and regulatory compliance for food contact applications. The transition from lab-scale formulations to large-scale manufacturing presents several technical hurdles, including maintaining emulsion stability during film processing, optimizing drying techniques to prevent emulsion breakdown, and ensuring uniform dispersion of oil droplets within the polymer matrix. Furthermore, regulatory approval for novel stabilizing particles and bioactive compounds used in these films remains a key consideration, requiring extensive safety evaluations to meet food industry standards. Addressing these challenges will be crucial in facilitating the commercial adoption of Pickering emulsion-based edible films as a viable alternative to conventional plastic packaging.

The results demonstrate that incorporating Pickering emulsions into biopolymeric edible films significantly improves their mechanical and barrier properties. In chitosan-based films, these emulsions reduce brittleness and enhance flexibility, thereby increasing durability and effectiveness in food preservation applications. In konjac glucomannan-based films, Pickering emulsions reinforce the structure and increase tensile strength without compromising flexibility, while also improving moisture resistance. However, optimizing emulsion composition, selecting suitable stabilizing particles, and balancing essential oil concentration remain critical challenges. Additionally, issues related to large-scale production, emulsion stability during film processing, and regulatory compliance must be carefully addressed to enable industrial application. Overall, Pickering emulsions offer a sustainable and effective technology with high potential to replace conventional plastics in food packaging.

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